CLIMATE CHANGE PROJECTION REPORT

INSIGHTS FROM CMIP6
MAY 2024

National Centre for Hydrology and Meteorology
Royal Government of Bhutan

CLIMATE PROJECTION REPORT OF BHUTAN

INSIGHTS FROM CMIP6 PROJECTIONS

NATIONAL CENTRE FOR HYDROLOGY AND METEOROLOGY
ROYAL GOVERNMENT OF BHUTAN
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National Centre for Hydrology and Meteorology

"Centre of Excellence in Hydrology, Meteorology and Cryosphere Science and Services"

Foreword

Bhutan has long been recognized for its proactive stance on environmental sustainability and climate resilience. As we stand on the precipice of unprecedented climate change, the importance of understanding and preparing for the future climate of Bhutan cannot be overstated. The Climate Model Intercomparison Project Phase 6 (CMIP6) offers a critical tool for assessing future climate projections, providing invaluable insights into the potential impacts of climate change on Bhutan. This report represents a culmination of rigorous scientific research and collaborative efforts aimed at deciphering the implications of CMIP6 projections for Bhutan's unique climate system. Bhutan's vulnerability to climate change is deeply intertwined with its geographic location, topography, and socio-economic characteristics. Moreover, Bhutan's economy, which is largely dependent on agriculture, hydropower, and tourism, is intricately linked to its natural resources, making it highly susceptible to climate variability and extremes. Rising temperatures are leading to the accelerated melting of glaciers, posing imminent risks to downstream communities and hydropower. The findings presented in this report shed light on the projected changes in temperature, precipitation patterns, and extreme weather events in Bhutan under different emission scenarios. These projections serve as a wake-up call, underscoring the urgent need for adaptive measures and climate-resilient strategies to safeguard Bhutan's ecological integrity and socio-economic well-being. Climate change is not a distant threat but a present reality, with tangible impacts already being felt across Bhutan. The updated climate projection is timely since Bhutan has embarked on the 13th Five Year Plan and other strategic development works. The projection will help different sectors plan their development activities factoring climate risks on them. NCHM hopes the projections will therefore be useful for national planning.

Karma Dupchu
Director

Acknowledgement

As we celebrate our efforts in preparing the climate projection report for Bhutan based on CMIP6 projections, it is with profound gratitude and appreciation that we extend our heartfelt acknowledgements to all those who have contributed to this endeavor. In particular, we would like to express our deepest gratitude to the RGOB-GCF-UNDP Project: Preparation of the National Adaptation Plan (NAP) for Bhutan, with a focus on the water sector, the United Nations Economic and Social Commission for Asia and the Pacific (UNESCAP), and the National Institute for Environmental Studies (NIES) Japan for their unwavering support, guidance, and collaboration throughout this journey.

The invaluable assistance provided by the NAP Readiness Project (2019-2024) has been instrumental in laying the groundwork for this report, facilitating capacity building initiatives, and fostering multi-stakeholder engagement. Their commitment to advancing climate resilience and adaptation efforts in Bhutan has served as a driving force behind our collective endeavors. We are also indebted to UNESCAP for their expertise in climate modeling, data analysis, and technical support, which have greatly enriched the quality and rigor of our report. Furthermore, we extend our sincere appreciation to NIES Japan for their invaluable contribution of downscaling, data, expertise, and technical assistance. NIES's support has been instrumental in enhancing the robustness and reliability of our climate projections, enabling us to provide comprehensive insights into the future climate of Bhutan.

In addition to our esteemed partners and collaborators, we would like to express our heartfelt gratitude to the individuals who have played a pivotal role in the preparation of this report. We would also like to extend our gratitude to Ms. Prangya, whose diligent efforts in preparing this report, data collection, analysis, and interpretation have been invaluable to the success of this project. Her meticulous attention to detail and unwavering dedication have been a driving force behind our research endeavors. We extend our deepest thanks to Mr. Yuji Masutomi (Ph.D) whose technical expertise, guidance, and support have been indispensable throughout the research process. Furthermore, we express our heartfelt thanks to Ms. Madhurima Sarkar-Swaisgood (Ph.D) for her invaluable contributions to the report, including her insights, expertise, and technical assistance. Finally, we extend our gratitude to all the stakeholders, experts, and contributors who have generously shared their knowledge, expertise, and data for the preparation of this report. Your collective efforts have played a crucial role in shaping the findings, recommendations, and insights presented herein. May this report serve as a valuable resource for policymakers, practitioners, and stakeholders as we work together to build a climate-resilient future for Bhutan and beyond.

List of Acronyms

°C	Degree Celsius
Avg	Average
CMIP5	Coupled Model Intercomparison Project Phase 5
CMIP6	Coupled Model Intercomparison Project Phase 6
CRU	Climate Research Unit
ECMWF	European Centre for Medium-Range Weather Forecasts
EE&C	Energy Efficiency & Conservation
ERA5	ECMWF Reanalysis
ESCAP	Economic and Social Commission for Asia and the Pacific
GDP	Gross Domestic Product
GHG	Green House Gas
GLOFs	Glacial Lake Outburst Floods
INDC	Intended Nationally Determined Contribution
IPCC	Intergovernmental Panel on Climate Change
IPCC AR6	Intergovernmental Panel on Climate Change Annual Report 6
LEDS	Low Emission Development Strategies
MoAL	Ministry of Agriculture and Livestock
MoENR	Ministry of Energy and Natural Resources
MoESD	Ministry of Education and Skills Development
MOICE	Ministry of Industry, Commerce and Employment
NAP	National Adaptation Plan
NDC	Nationally Determined Contribution
NEECP	National Energy Efficiency & Conservation Policy
NRS	National REDD+ Strategy

PyGEM	Python Glacier Evolution Model
RCP	Representative Concentration Pathways
REDD+	Reducing Emissions from Deforestation and forest Degradation
SANP	Skills Assessment for the NAP
SSP	Shared Socio-economic Pathways
Tmax	Maximum temperature
Tmin	Minimum temperature
UN	United Nations
UNDP	United Nations Development Programme

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Executive Summary

Climate change-induced hazards are serious threat to Bhutan primarily because of its fragile mountain ecosystem and socio-economy. The mountainous terrain is highly vulnerable to diverse extreme weather events such as floods, landslides, seasonal drought, and glacial lake outburst floods (GLOFs). As a result of global warming the mountain glaciers are retreating resulting in fluctuations in water availability as well as increasing the risk of GLOFs, risking lives and properties. The impacts of such changes are clearly visible through the increased frequency of extreme events during the recent decades, advocates for more attention to understand the future climate for efficient adaptation plans.

Climate change is a reality in Bhutan which is visible through the increase in temperature since 1960. The increase in maximum and minimum temperature is sharper in the recent decades (1991-2020) mainly contributed by the GHG emission and the global socioeconomic development with frequent occurrence of high temperature related extreme events. A greater magnitude of increase in both maximum and minimum surface air temperature is observed in the north and western part of Bhutan in the recent past. The Intergovernmental Panel on Climate Change's (IPCC) sixth assessment report highlighted that temperatures are increasing in the Himalayas and increases with altitudes. The long-term decadal change (1950-2020) shows a decreasing trend in precipitation until 1970 after which there has been increase in precipitation in Bhutan. From 1990 onwards, the rate of increase has been higher. The IPCC sixth assessment report projects an increase in heavy precipitation in the Himalayan part of Bhutan in the 21st century.

According to the latest climate projection data, both seasonal and annual precipitation is likely to increase across the country until 2100. The increase is more in the higher emission scenarios. More increase is likely in the north, west, north-west, and south-western parts of the country with enhanced risk of floods and related events. However, some areas in the east and south-east may receive less precipitation than long-term normal until 2060 indicating the probability of seasonal drought or water scarcity situation in near and mid-future.

Both Maximum and minimum temperatures are likely to increase across the country until 2100. The increase is more in the higher emission scenarios and in long-term. The increase in minimum temperature is more than that of maximum temperature, especially in the long-term. Both maximum and minimum temperatures are likely to increase more in the northern and central part of the country enhancing the risk of heatwave like situation and speeding up glacial melt.

The glacial mass balance is likely to decrease until 2100 mainly due to global warming and resultant increase in temperature. The decrease is more in the higher emission scenarios. Among the major river basins, Manas basin is likely to be affected most due to less glacial mass balance. The glacier run-off is likely to increase in near and mid-term due to more glacial melt but decrease in long-term. This is likely to enhance the water availability in the river basins in the near and mid-term and but might enhance the risk of GLOFs. In the long term, less run-off might enhance the risk of seasonal drought especially in areas where rainfall is also likely to be less. Among the river basins Wang Chhu is likely to be impacted most due to reduction in glacial run-off.

The impacts of climate change are unevenly distributed across sectors and populations and their pre-existing vulnerabilities make it challenging to prepare for and cope with the changes. The major economic sectors such as agriculture (including livestock and forestry), hydropower and water supply, and construction which contribute significantly to the national GDP are under threat due to climate change. The highly populated areas in Bhutan are expected to experience increased rainfall and temperature and their impacts. The major rice producing areas in the east are likely to face water scarcity while in the west, south and north they might face flood like situation.

Climate-induced disaster risk can outpace the country’s resilience. Hence, risk-informed adaptation measures targeted to the vulnerable sectors and communities can help avoid losses caused by disasters and enhance the resilience of the country. Identifying the priority areas and continued investment in those areas is needed to strengthen disaster resilience locally and nationally. The policy decisions based on science and evidence can enhance both social and economic outcomes.

1 Introduction

Bhutan is a landlocked country located in the southern slope of the eastern Himalayas within the Hindu-Kush Mountain range. Bhutan’s climate is diverse and abruptly changes due to changes in elevation and topography. The southern part of the foothills of the Himalayas has a sub-tropical climate with fairly even temperature between 15°C and 30°C throughout the year and total annual rainfall of 2000 to 5000 mm. The central part with valleys has cool winters and hot summers and the northern part has snowcapped mountains with an alpine climate of cold winter and cool summer climate and around 400mm of annual precipitation[1,2]. Precipitation is mainly brought by the south-west monsoon from June to September, however, it varies widely across the country. There is substantial variation in temperature and precipitation within these broad climate zones. The variation in the micro-climatic condition depends on the aspect of the valleys, steepness of the slopes, altitude, and other physiographic factors.

Although Bhutan has 70% of its total land area under forest cover and is a net sequester of Green House Gas, the impacts of climate change are becoming increasingly visible, many times which is transboundary. Bhutan's geography makes it particularly susceptible to the impacts of climate change. Its mountainous terrain renders it highly vulnerable to diverse extreme weather events such as floods, landslides, and glacial lake outburst floods (GLOFs). Bhutan is also frequently exposed to seasonal droughts, windstorms, and heavy snowfall. Heavy rainfall is the predominant cause of floods and landslides in Bhutan.

The Intergovernmental Panel on Climate Change’s (IPCC) sixth assessment report highlighted that temperature is increasing in the Himalayas and increases with altitudes. Most of the mountain glaciers have retreated since the early 21st century. Seasonal changes such as the early onset of spring are increasingly being observed. Global warming has already contributed to the increased streamflow in the low-elevation mountain catchment areas [3]. While unpredictable rainfall and fluctuating glacial melts are causing floods and landslides in some parts of the country, while drying up of water resources in others. The impacts of such changes are quite clearly visible through the

[1] Bhutan (2016). Bhutan State of the Environment Report. URL: http://www.nec.gov.bt/nec1/wp-content/uploads/2016/07/Bhutan-State-of-Environment-Report-2016.pdf

[2] ICIMOD, 2016. Bhutan Climate+Change Handbook. Available at https://lib.icimod.org/record/32399/files/icimodBhutanClimate016.pdf

[3] https://www.ipcc.ch/report/ar6/wg1/downloads/factsheets/IPCC_AR6_WGI_Regional_Fact_Sheet_Mountains.pdf

occurrence of extreme events in Bhutan. A decadal analysis shows that the number of climate related extreme events in Bhutan increased many folds in the last decade compared to the previous decades (*Figure 1*).

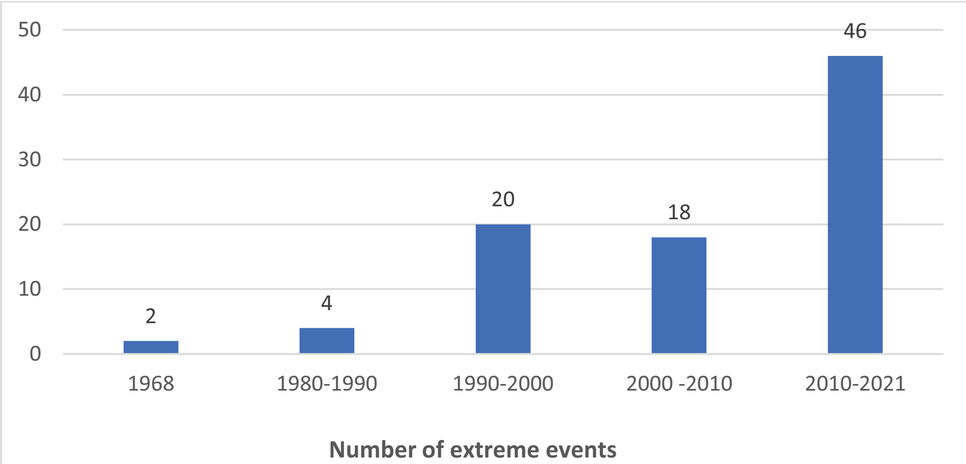

Figure 1 Number of extreme events in Bhutan (until Aug'2021) [4,5]

The key socio-economic sectors of Bhutan are climate-sensitive and face multifaceted challenges due to climate change and its impacts. The major economic sectors such as agriculture (including livestock and forestry), hydropower and water supply, and construction which contribute 20.4%, 14.3%, and 10.8% to national GDP respectively[6] are under threat due to climate change. Glacial retreat is affecting the water availability impacting agricultural productivity, energy production, and drinking water availability with cycles of flooding during monsoons and very low flows and drying streams during other seasons. Heavy precipitation leads to floods and landslides which directly impact the population, agriculture, hydropower, and other infrastructure. The forest and biodiversity of Bhutan play an important role in the country's social, cultural, economic, and physiographic conditions and they are being affected by climate change-related impacts. Economically Bhutan depends heavily on nature through agriculture, hydropower, and tourism. Moreover, the rural communities which make up around 67% country's households[7] largely depend directly or indirectly on the forest and nature-based goods and services.

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[4] Compendium of climate and hydrological extreme events in Bhutan since 1968 from Kuensel, NCHM.

[5] Compendium of climate and hydrological extreme events in Bhutan (2017 -2021), NCHM.

[6] https://www.mof.gov.bt/wp-content/uploads/2022/06/Budget-Report-for-FY-2022-23-in-English.pdf

[7] https://www.nsb.gov.bt/wp-content/uploads/dlm_uploads/2023/01/METADATA-ON-2022-BLSS.pdf

Hence, to reduce the increasing risks it is important to understand and foresee future risk scenarios to guide optimal and contextual adaptation and mitigation pathways - from national to local levels. The global climate models are unable to predict the local impacts of future climate especially for a small country like Bhutan. Hence, there is a need to downscale climate projection to a sub-national level in order to foresee unidentified risks and develop risk-informed adaptation and mitigation strategies.

2 Methodology

To support the implementation of National Adaptation Plan of Bhutan there was a need to understand the future climate and related risks based on CMIP6 climate projection models and scenarios. For this purpose, following two major tasks were undertaken as part of this study.

- Downscaling CMIP6 climate projection data (100km) to 1 km resolution
- Assess the climate risk for the relevant socio-economic sectors

Downscaling CMIP6 data involves development of sub-national climate projection datasets with 1km spatial resolution for Bhutan based on the global data (100 km spatial resolution). Two primary climate variables, namely Temperature and Precipitation are chosen to understand the future climate risks in different timescales. CMIP6 data is developed for five Shared Socio-economic Pathways (SSPs) which are designed based on anticipated changes in the socio-economy along with the climate in the future. Among them, three namely SSP1 2.6, SSP2 4.5 and SSP3 7.0 were chosen for this study. SSP1 2.6 is considered as the best-case scenario which considers the policies and pathways related to sustainable development in the future. SSP2 4.5 is considered as the moderate-case scenario as it represents the current socio-economic development pattern and related emissions. SSP3 7.0 is considered as the worst-case scenario as it depicts a scenario where both adaptation and mitigation are challenging. Three different timescales were chosen for this study namely Baseline (1971-2000), near-term (2021-2040), mid-term (2041-2060) and long-term (2081-2100).

The climate risk assessment has used the downscaled climate projection data as a proxy of the hazards prevalent in Bhutan and identify the risk hotspots, assess the exposure of climate sensitive sectors to the hazards. For glacier related analysis CMIP5 climate projection datasets from High-mountain Asia rasterized PyGEM glacier projections were used. Three climate scenarios RCP2.6, RCP4.5 and RCP8.5 were considered in the analysis for three time periods as mentioned above. Anticipated changes in glacial mass balance and glacier runoff were used to identify the hazard risk hotspots and exposure of relevant sectors were assessed.

2.1 Downscaling of climate projection data

2.1.1 Selection of historical climate data

The WorldClim historical climate data is used in this study for bias correction of the CMIP6 climate model data. WorldClim data is developed from spatially interpolated monthly climate data for global land areas at a very high spatial resolution (approximately 1 km2). It includes monthly estimation of the variables aggregated across a target temporal range of 1970–2000, using data from between 9000 and 60 000 weather stations. The data is preferred over CMIP6 historical data considering the topographical nature of Bhutan.

2.1.2 Selection of climate models for future climate data

The future climate data is sourced from the CMIP6 global dataset. 10 climate models were chosen from the CMIP6 models based on the primary and secondary climate models specified by ISIMiP[8]. The selection of primary models based on parameters such as the process representation, structural independence, climate sensitivity, performance in the historical period. According to ISIMiP, the better-performing CMIP6 models are AWI-CM-1-1-MR, CESM2, CESM2-WACCM, GFDL-CM4, GFDL-ESM4, HadGEM3-GC31-LL, MPI-ESM1-2-HR, MPI-ESM1-2-LR, MRIESM2-0, SAM0-UNICON and UKESM1-0-LL. Additionally, based on the availability of the required variables GFDL-ESM4, MPI-ESM1-2-HR, MRI-ESM2-0 and UKESM1-0-LL as potential primary models. Another model providing data for potential variables is IPSL-CM6A-LR. Among these five models GFDL-ESM4, MPI-ESM1-2-HR, MRI-ESM2-0 shows low climate sensitivity and IPSL-CM6A-LR, UKESM1-0-LL show high climate sensitivity. Apart from them, 5 other secondary climate models were selected based on the criteria mentioned above. Table 2 provides the details of the CMIP6 climate models included in ISIMIP3b and chosen for this study.

[8] https://www.isimip.org/documents/413/ISIMIP3b_bias_adjustment_fact_sheet_Gnsz7CO.pdf

Table 1 Specs of CMIP6 climate models included in ISIMIP3b

Model	Group	Resolution	Member	piControl	ps	sfcWind
GFDL-ESM4	primary	1.0°	r1i1p1f1	0001–0500	available	available
IPSL-CM6A-LR	primary	2.0°	r1i1p1f1	1870–2369	available	available
MPI-ESM1-2-HR	primary	1.0°	r1i1p1f1	1850–2349	available	available
MRI-ESM2-0	primary	1.0°	r1i1p1f1	1850–2349	proxy	available
UKESM1-0-LL	primary	2.0°	r1i1p1f2	1960–2459	available	available
CanESM5	secondary	2.0°	r1i1p1f1	5201–5700	proxy	available
CNRM-CM6-1	secondary	1.0°	r1i1p1f2	1850–2349	proxy	proxy
CNRM-ESM2-1	secondary	1.0°	r1i1p1f2	1850–2140	proxy	proxy
EC-Earth3	secondary	0.5°	r1i1p1f1	2259–2758	proxy	available
MIROC6	secondary	1.0°	r1i1p1f1	3200–3699	proxy	proxy

2.1.3 Downscaling method

The monthly global data (100km) on future projection of precipitation and temperature is collected from the repository of the National Institute for Environmental Studies (NIES), Japan for each of the 10 models mentioned above and 3 scenarios for 1971 – 2100. From the global data, the data for Bhutan is extracted. 30 years average (the time periods of 1970-2000, 2021-2040, 2041-2060 and 2081-2100) of each of the variables are done for each month. The same process was repeated for the historical data (WorldClim) for the period of 1970-2000. Bias correction is done for the 30 years average data for each month calculating the difference between the WorldClim observational data and climate model data for 1971-2000 and adjusted for the other time periods. The downscaling is done using bilinear interpolation. All the processes were automatized using shell programming interface. The same process was repeated for all the 10 selected models and all the variables. Finally, the ensemble of models was prepared taking the average of all the models for each variable.

2.2 Climate risk assessment

The climate risk assessment has been carried out based on the downscaled climate projection data. The hazard trends are assessed for each variable, each scenario and each time period. The hazards are categorized based on the range of values into low, medium and high hazard risk. The exposure analysis is done by overlaying the gridded hazard data of low, medium and high categories with the sectoral data using the methodology demonstrated in *Figure 2*.

For population exposure gridded population data from WorldPop has been used. Population exposure values are determined by overlaying the spatial variation of the 100-meter gridded population layers on the low, medium and high to very high-risk hazard zones. The data on the agricultural areas were collected from the stakeholders and subsequently overlaid with different hazard risk zones to assess the exposure. For rice production FAO MAPSPAM data on rice production was used to overlay on the hazard data. Likewise, the exposure of the hydropower plants to changing levels of glacial runoff was calculated through overlaying hydropower plant's locations with the glacial water availability per river basin and sub-basin.

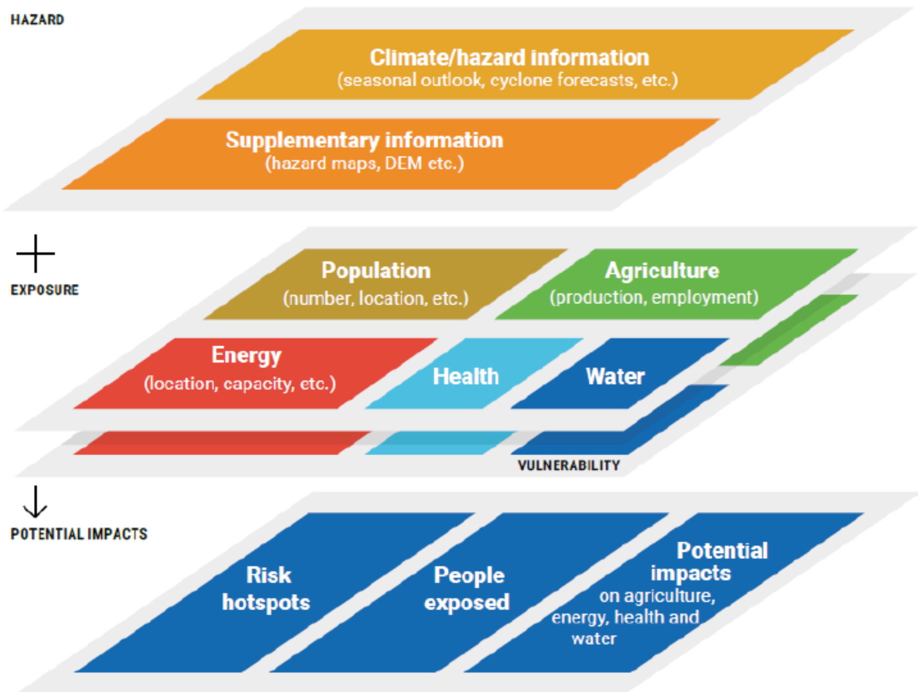


Figure 2 Climate risk assessment methodology using downscaled climate projection data

3 Historical climate trends

The increase in temperature has been seen in Bhutan since 1960; with minimum temperatures increasing at a faster rate than maximum temperatures[9]. The observational data between 1997 – 2017 confirms this trend[10]. The observed climatology derived from CRU data shows that the southern part of the country has a higher temperature, but decadal analysis of the temperature as derived from ERA5 reanalysis shows that a greater magnitude of positive change both in maximum and minimum surface air temperature in the north and western part of Bhutan than south in the recent past (*Figure 3* and *Figure 4*)

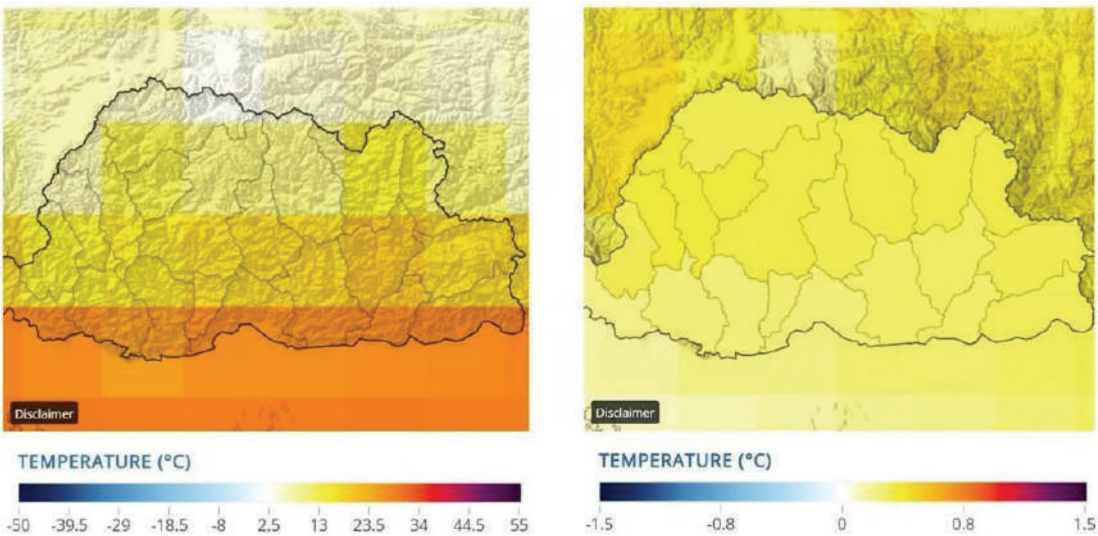


Figure 3 Observed climatology of average maximum surface air temperature 1991-2020 (left) and average annual maximum surface air temperature trend per decade 1971-2020 (right) in Bhutan [11,12]

[9] https://climateknowledgeportal.worldbank.org/sites/default/files/2021-08/15874-WB_Bhutan%20Country%20Profile-WEB.pdf

[10] https://www.nchm.gov.bt/attachment/ckfinder/userfiles/files/Analysis%20of%20Historical%20Climate%20and%20Climate%20Change%20Projection.pdf

[11] https://climateknowledgeportal.worldbank.org/country/bhutan/trends-variability-historical

[12] https://climateknowledgeportal.worldbank.org/country/bhutan/climate-data-historical

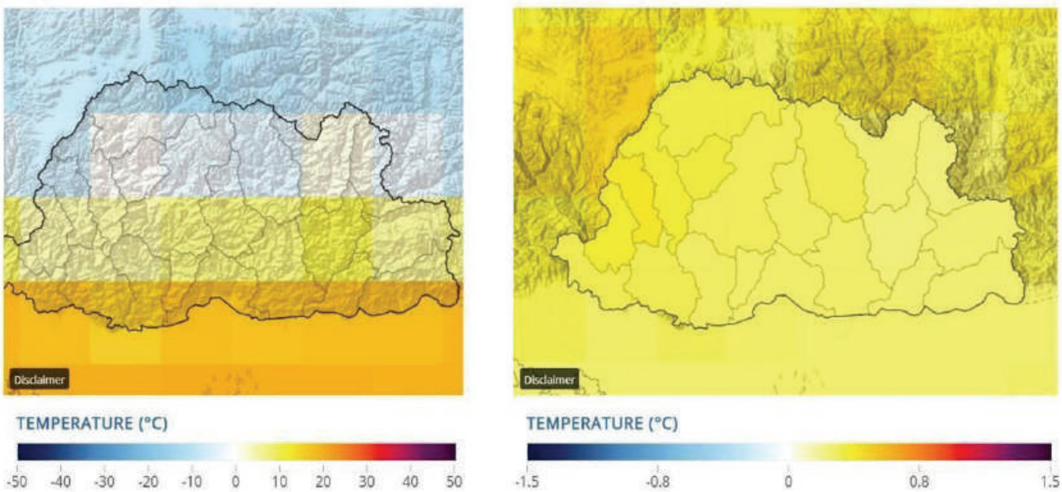
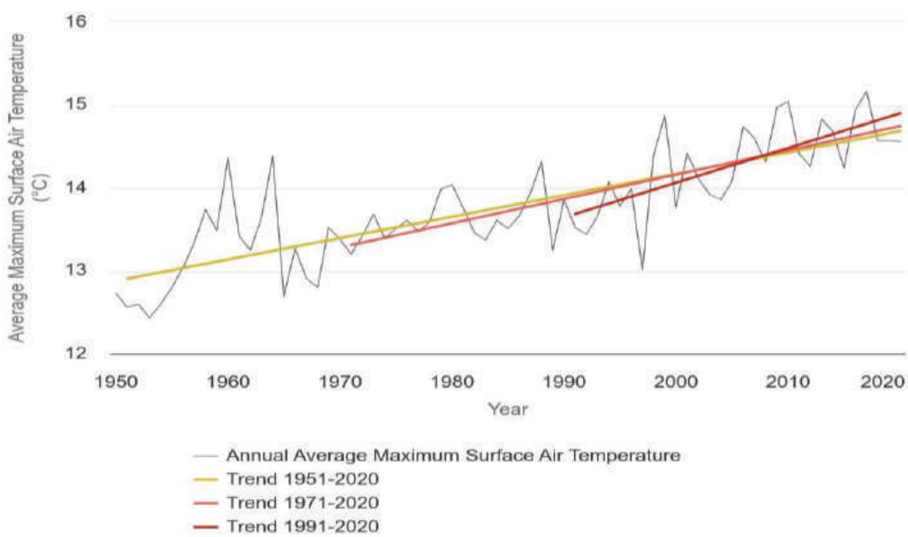


Figure 4 Observed climatology of average minimum surface air temperature 1991-2020 (left) and average annual minimum surface air temperature trend per decade 1971-2020 (right)

The increase in temperature is sharper in the recent decades (1991-2020) mainly contributed by the GHG emission and the socioeconomic development. The recent decades have also witnessed a greater number of high air temperature related extreme events (such as heatwaves) with maximum temperature significantly deviating from the mean monthly maximum temperature over the climatology of 1991-2020 (*Figure 5*). The decadal change in the minimum temperature is sharper than the maximum temperature. A higher number of extreme events related to low temperature (like cold waves) were observed in the historical past which confirms the increase in minimum temperature in the recent decades (*Figure 6*).



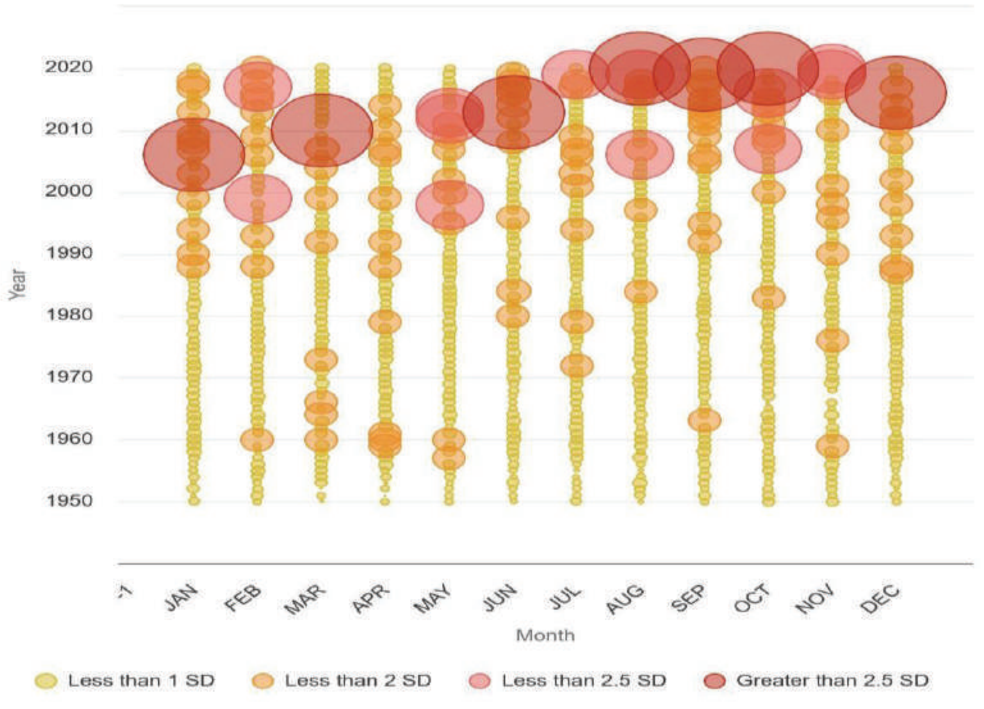
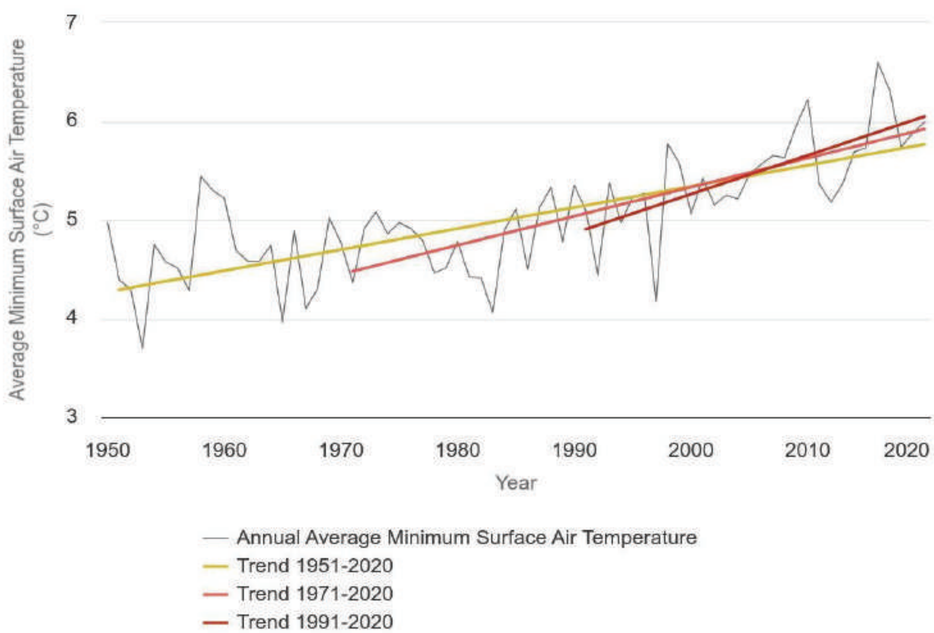


Figure 5 Average maximum surface air temperature trends with significance trend per decade, 1951-2020 (top) and change in event intensity of maximum of daily maximum temperature, 1951-2020 (bottom) [9,10]



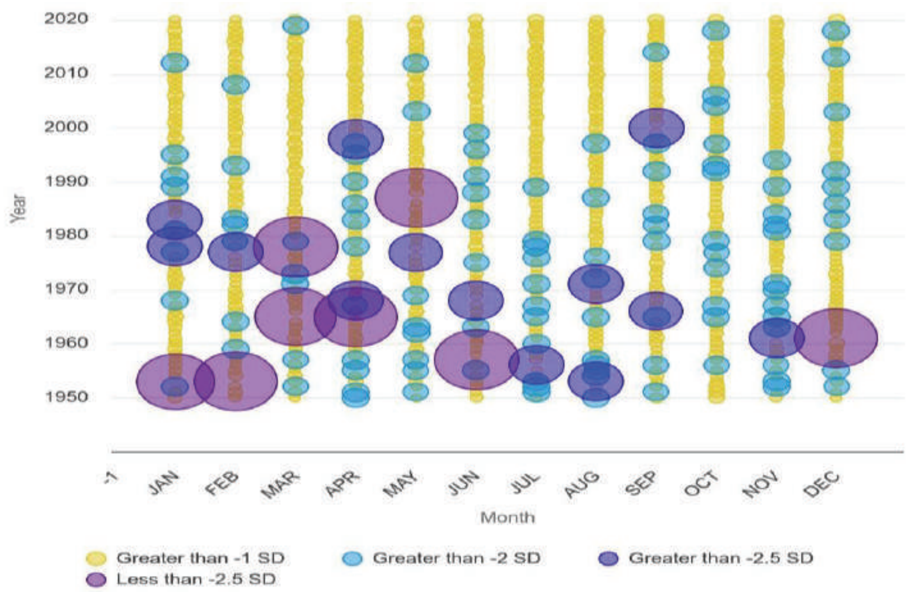


Figure 6 Average minimum surface air temperature trends with significance trend per decade, 1951-2020 (top) and change in event intensity of minimum of daily minimum temperature, 1951-2020 (bottom)

In general, the annual precipitation is higher in the southern part of the country, which decreases as we move northwards. The annual precipitation trend per decade shows that some of the districts in the central and south-eastern parts of Bhutan receiving more rainfall than the other parts of the country (Figure 7). The decadal trend shows that in long term (1950-2020) annual precipitation has decreased. However, in the recent decades (1970 onwards) there has been increase in precipitation in Bhutan. From 1990 onwards, the increase has been steeper. The intensity of extreme events related to precipitation does not show any significant trend (Figure8). The IPCC sixth assessment report projects an increase in heavy precipitation in the Himalayan part of Bhutan in the 21st century[13][14]. Increases in both annual and summer monsoon are likely across the rest of the country with larger interannual variability. The report also highlighted that the snow cover in the high mountain Asia has is reducing since early 21st century and glaciers have thinned, retreated, and lost mass since the 1970s. Increasing temperature and precipitation in this region can increase the occurrence of glacial lake outburst floods and landslides over moraine-dammed lakes.

[13] https://www.ipcc.ch/report/ar6/wg1/downloads/factsheets/IPCC_AR6_WGI_Regional_Fact_Sheet_Asia.pdf
[14] https://www.ipcc.ch/report/ar6/wg1/downloads/factsheets/IPCC_AR6_WGI_Regional_Fact_Sheet_Mountains.pdf

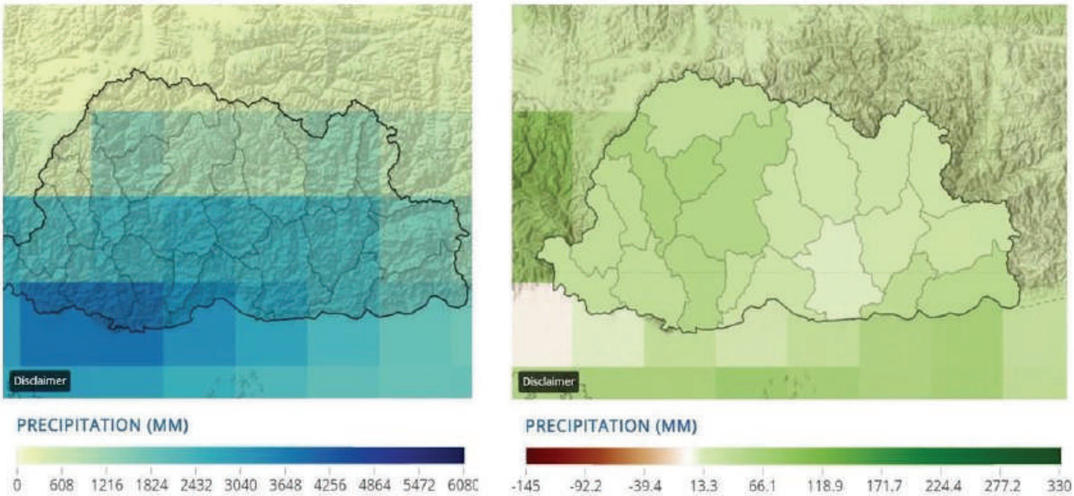
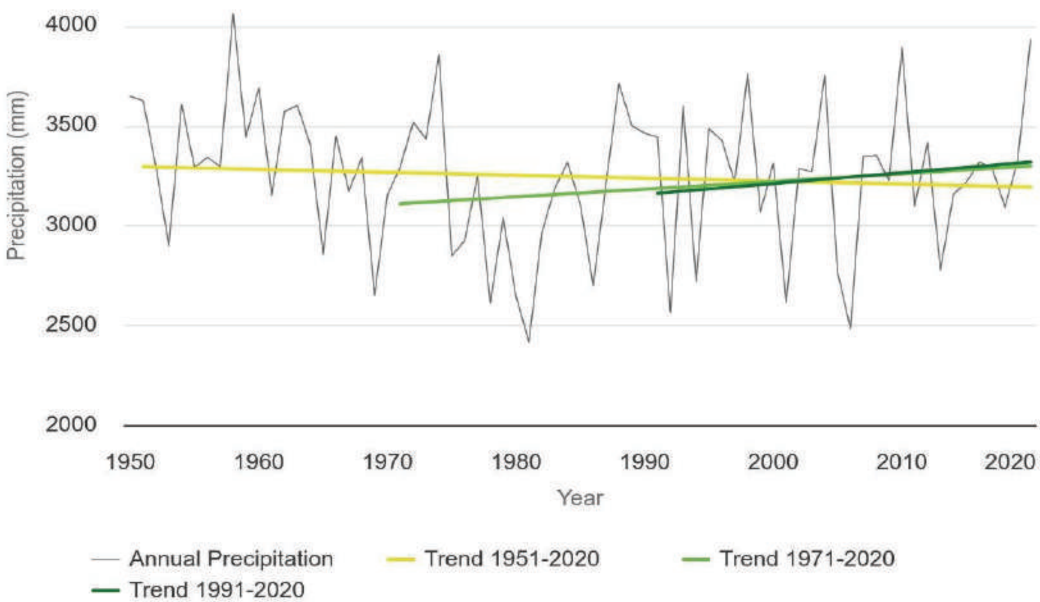


Figure 7 Observed climatology of precipitation in Bhutan (1991-2020) (left) and Annual precipitation trend per decade (1971-2020)



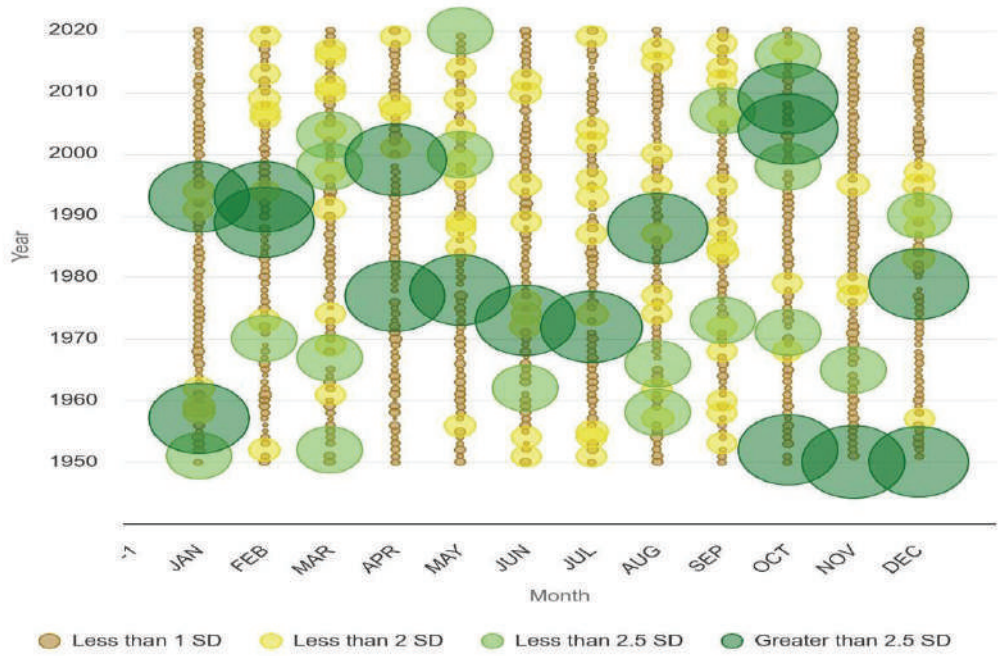


Figure 8 Precipitation annual trend with significance of trend per decade, 1951-2020 (top) and change in event intensity of average largest 5-day cumulative precipitation (bottom), 1951-2020 [9,10]

4 Future climate projection

4. 1 Precipitation

4. 1.1 Annual precipitation

Figure 9 shows the projected spatial distribution of total annual precipitation under baseline and changes in total annual precipitation in the near-term (by 2040) under different SSPs. Under baseline scenario the southern part of Bhutan receives the highest rainfall. Rainfall is relatively less towards the northern mountainous parts.

Under all the three climate change scenarios, although the spatial distribution of changes in rainfall by 2040 is similar, the variation from the baseline is different. North, west, central and south-western districts are likely to receive more precipitation than baseline. Under SSP1 2.6 scenario the highest increase is likely in Wangdue Phodrang followed by Gasa, Punakha, Bumthang and Thimphu. Whereas the east and south-eastern districts (Pemagatshel, Samdrup Jongkhar, Sarpang, Trashigang and Trashi Trashi Yangtse) are likely to receive less precipitation than the baseline. Under SSP2 4.5 and SSP 3 7.0 scenarios, the increase in precipitation is less compared to SSP1 2.6. However, Punakha, Gasa, Samtse, Thimphu, Paro and Haa are some of the districts where the increase in precipitation is more (*Annex 2*).

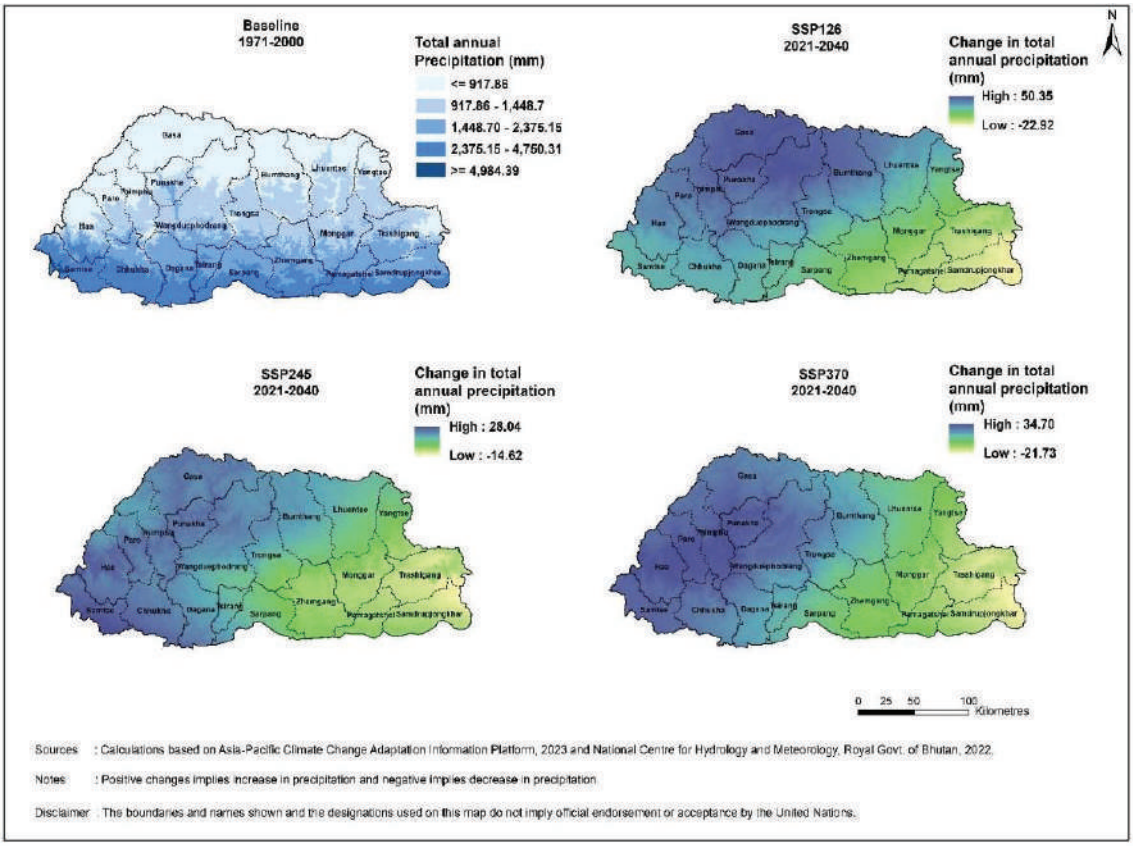


Figure 9 Total annual precipitation under baseline scenario and change in total annual precipitation from baseline under SSP1 2.6, SSP2 4.5 and SSP3 7.0 scenario by 2040

By 2060, the precipitation is likely to increase across the country although the increase is more in the north, west, central and south-western districts and less in east and south-eastern districts. Under SSP1 2.6, the total annual precipitation may increase up to 82mm in Punakha (Figure 10). Under SSP2 4.5 and SSP3 7.0 the projected increase is less than SSP1 2.6 across the country. However, by 2100 the increase in more in the higher emission scenario. However, Wangdue Phodrang, Gasa, Punakha, Thimphu, Paro, Dagana, Chhukha, Trongsa, and Samste are expected to receive comparatively higher rainfall than the other districts in all three scenarios (Also see Annex2).

By 2100, all the districts are likely to receive at least 56mm more total annual precipitation than baseline. More than 100mm increase is likely in Haa, Samtse, Paro, Punakha, Thimphu, Chhukha, Gasa and Wangdue Phodrang. Under SSP2 4.5 the highest increase is likely in Punakha (171 mm) followed by Gasa, Thimphu, Paro, Bumthang and Wangdue Phodrang which are likely to receive around 150mm more precipitation than the baseline. Under the worst-case scenario, all the districts are likely to receive at least 300mm more precipitation from the baseline with the highest increase in Punakha *(Figure 11*) (*Also see Annex2*).

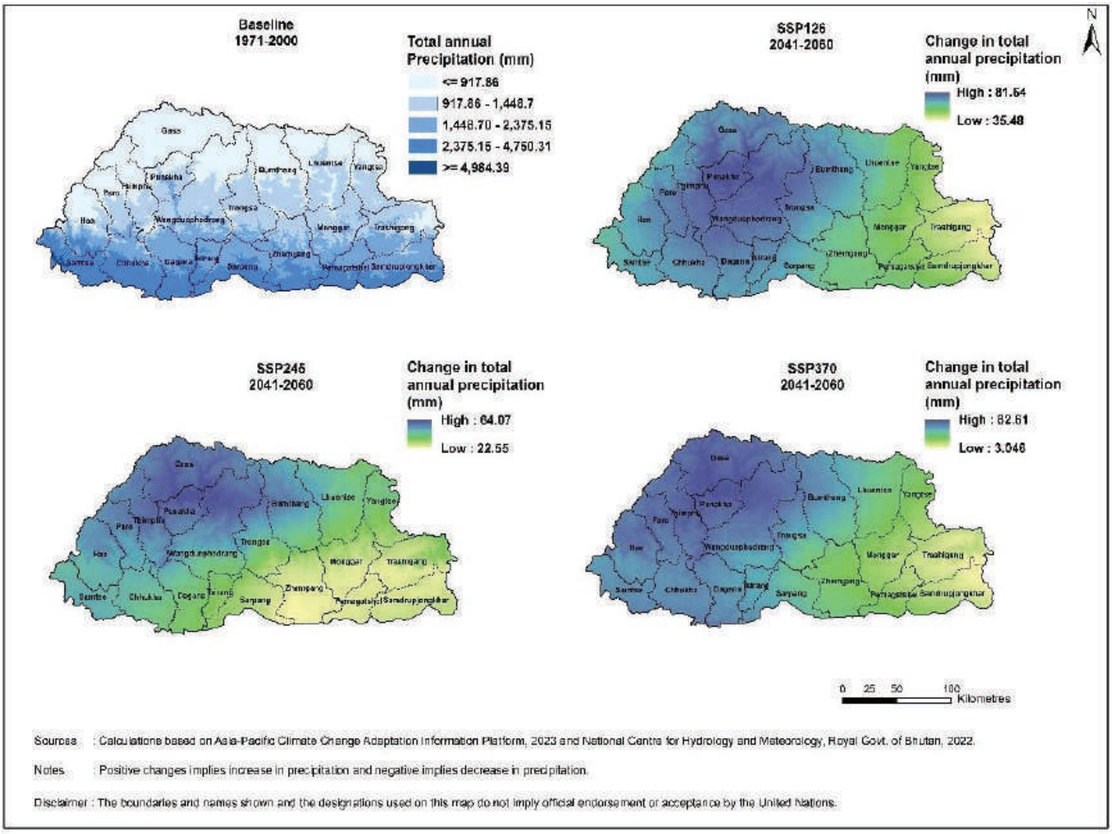


Figure 10 Total annual precipitation under baseline scenario and change in total annual precipitation from baseline under SSP1 2.6, SSP2 4.5 and SSP3 7.0 scenario by 2060

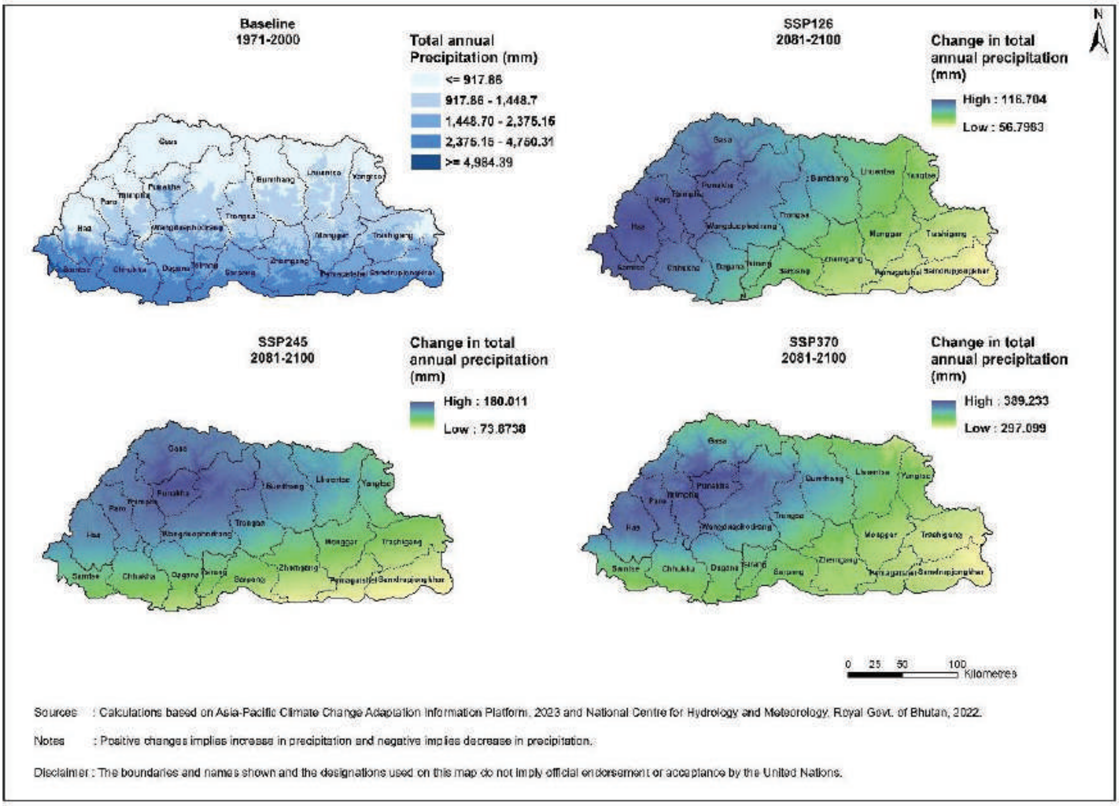


Figure 11 Total annual precipitation under baseline scenario and change in total annual precipitation from baseline under SSP1 2.6, SSP2 4.5 and SSP3 7.0 scenario by 2100

4.1.2 Precipitation in monsoon and winter season

Monsoon precipitation by 2040

June to September is the monsoon season in Bhutan which receives more than 70% of the annual rainfall. Like annual rainfall, the southern districts receive the maximum rainfall during the monsoon season. In the near-term (2040), the eastern and south-eastern districts namely Trashigang, Samdrup Jongkhar, Pema Gatshel, Monggar are likely to face a slight decrease (by up to 30 mm) in monsoon precipitation under the worst-case scenario. The span of the area with the likelihood of decreased precipitation from baseline expands under SSP2 4.5 scenario. Monsoon precipitation is likely to increase in the rest of the districts across all scenarios by 2040 and by up to 100 mm under the worst -case scenario. The highest increase is likely in the central and south-western districts such as Samtse, Chhukha, Haa, Dagana, Wangdue Phodrang. The southern districts which receive the highest rainfall in Bhutan are already flood-prone.

Paro and Thimphu are likely to experience around 100 mm increase in precipitation under the worst-case scenario. The monthly change in precipitation for the monsoon months in Bhutan follows the seasonal pattern. Among the monsoon months, the highest increase is likely in June and July. The monthly precipitation is likely to increase across the country in all the monsoon months, but the eastern districts are likely to receive less precipitation from the baseline in all months except for July (Figure 12 and Figure 13).

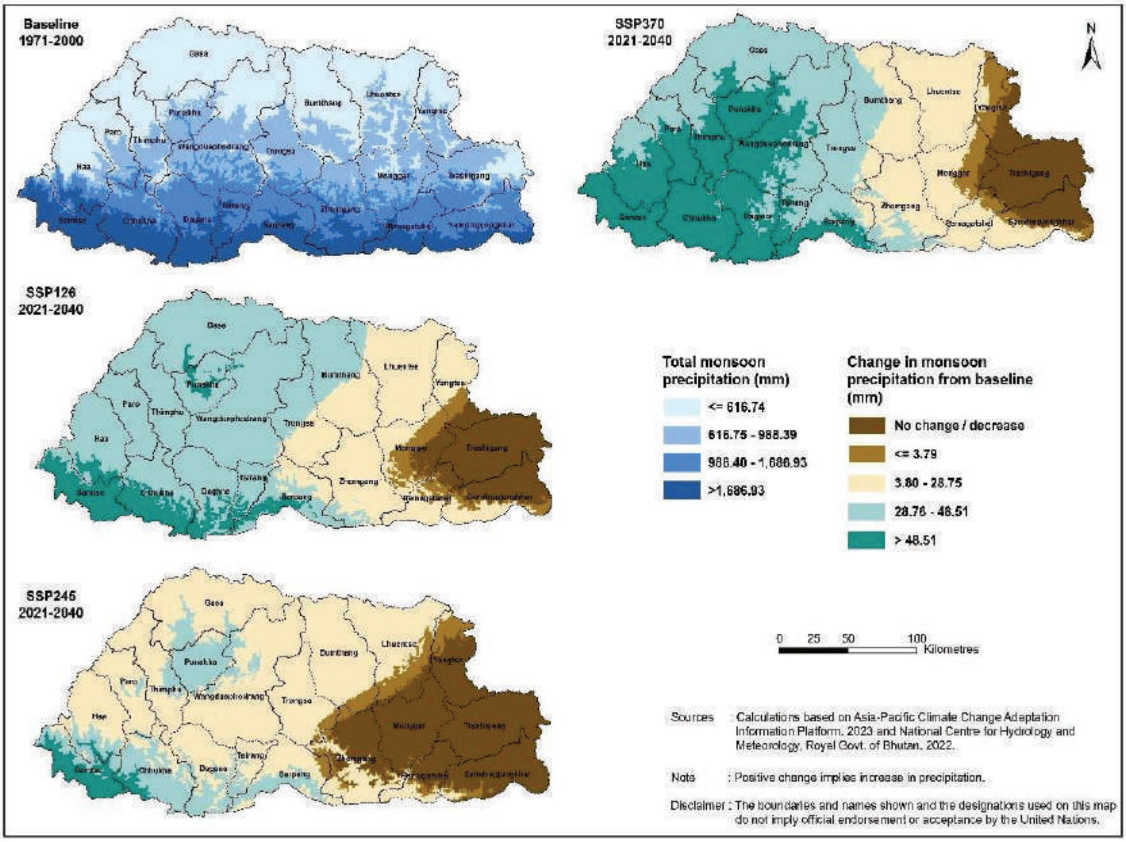
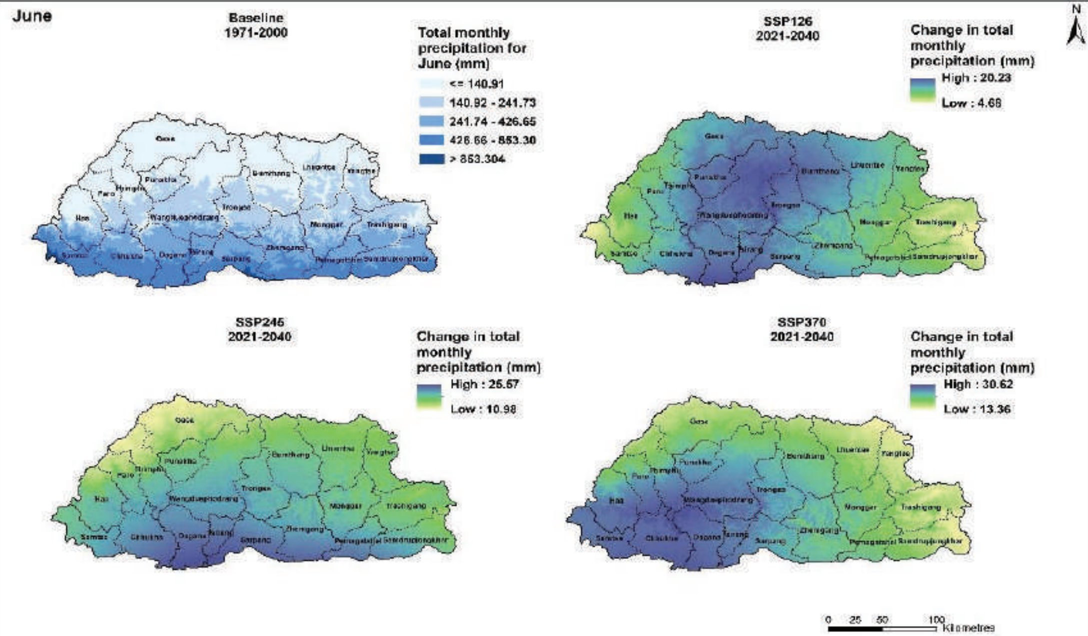


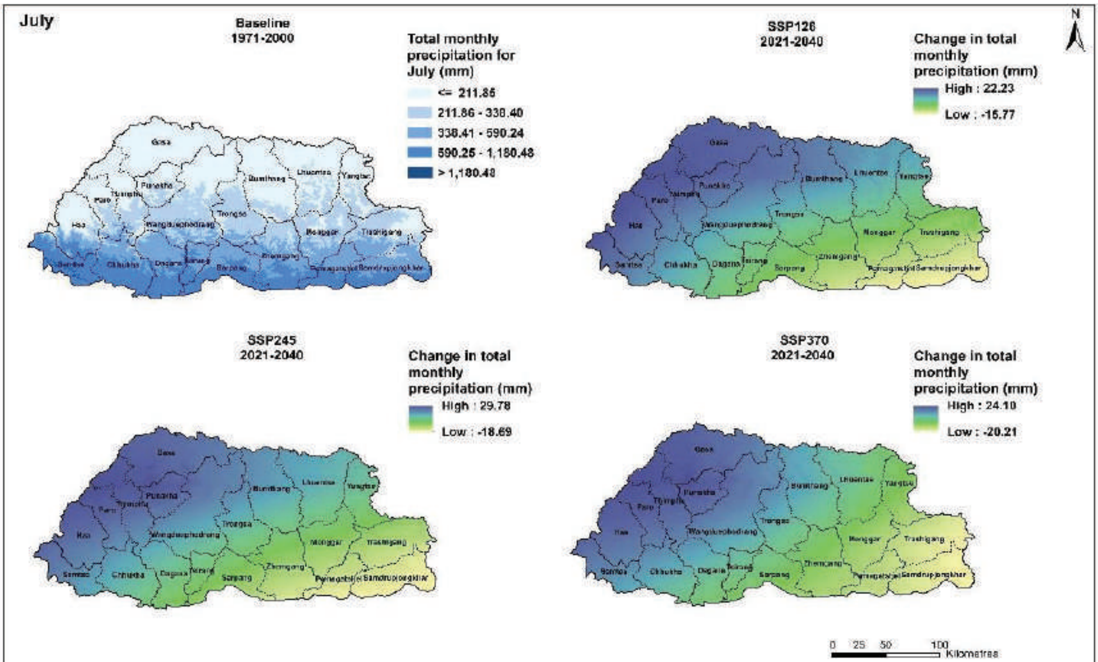
Figure 12 Total monsoon precipitation under baseline scenario and change in total monsoon precipitation from baseline under SSP1 2.6, SSP2 4.5 and SSP3 7.0 scenario by 2040



Sources : Calculations based on Asia-Pacific Climate Change Adaptation Information Platform, 2023 and National Centre for Hydrology and Meteorology, Royal Govt. of Bhutan, 2022.

Notes : Positive changes implies increase in precipitation and negative implies decrease in precipitation.

Disclaimer : The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations.



Sources : Calculations based on Asia-Pacific Climate Change Adaptation Information Platform, 2023 and National Centre for Hydrology and Meteorology, Royal Govt. of Bhutan, 2022.

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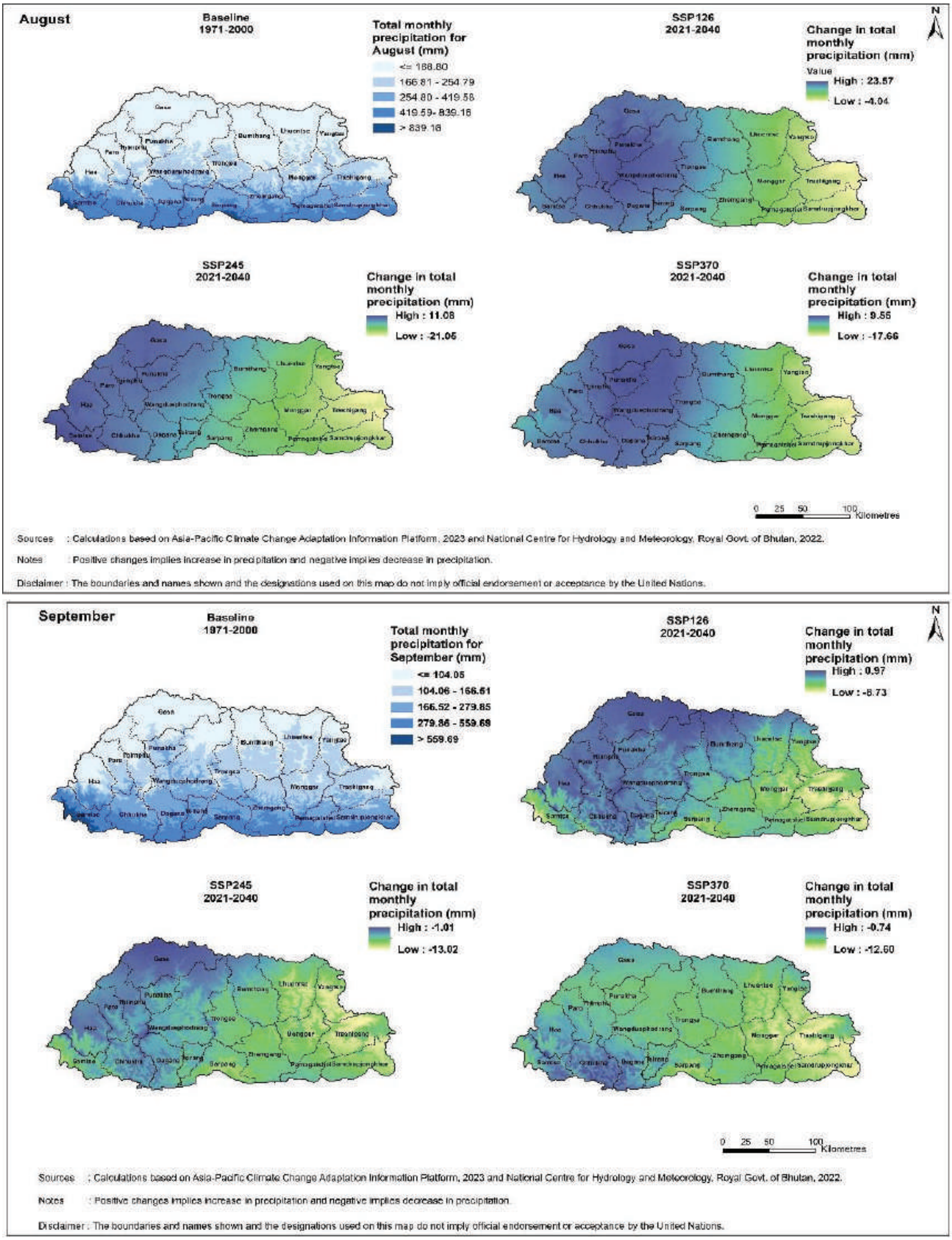


Figure 13 Total precipitation for June, July, August, September under baseline scenario and change in total precipitation for June, July, August and September from baseline under SSP1 2.6, SSP2 4.5 and SSP3 7.0 scenario by 2040

Winter precipitation by 2040

The winter rainfall is generally weak in Bhutan and mostly in form of snow, especially in the northern mountainous regions. The winter rainfall trend is analyzed for the months of December, January and February. Under SSP1 2.6 and SSP2 4.5 scenario all the districts are likely to experience an increase in precipitation of varying levels. The highest increase is likely in eastern (in Trashi Yangtse ~30mm) and south-eastern districts (in Samdrup Jongkhar~34mm) under SSP1 2.6 and SSP2 4.5 respectively. Under SSP3 7.0, the central to western half of the country is likely to experience no change or slight decrease in winter precipitation. The maximum decrease in winter precipitation is likely for Gasa (by ~8mm) under SSP3 7.0 scenario, but eastern half of the districts are likely to receive more precipitation (up to 35mm) by 2040 (*Figure 14*).

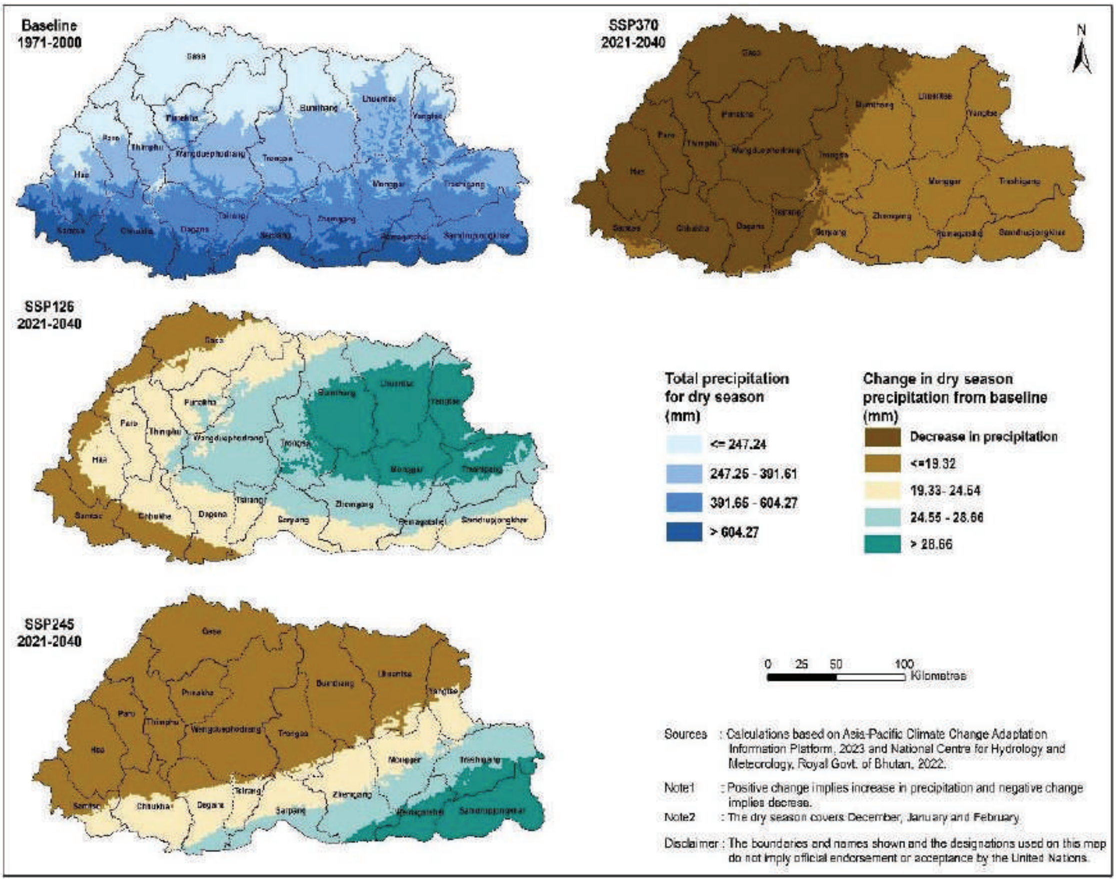


Figure 14 Total precipitation in the dry season under baseline scenario and change in total precipitation in dry season from baseline under SSP1 2.6, SSP2 4.5 and SSP3 7.0 by 2040

Monsoon precipitation by 2060

By 2060 the spatial distribution of the change in monsoon precipitation is likely to be like that of 2040. Most of the districts in the central to western part of the country are likely to get more precipitation than baseline. The maximum increase in precipitation is likely to be just over 100 mm under SSP3 7.0 in Samtse. Other adjoining southern districts are also likely to experience a high increase in precipitation under all climate change scenarios. Trashigang is likely to receive less precipitation than baseline under all scenarios by 2060. Paro and Thimphu are likely to experience more than 70mm increase in precipitation under the worst-case scenario. The sub-national monthly precipitation pattern follows the seasonal pattern, except SSP1 2.6 and SSP2 4.5 for the month of June. In June the highest increase in precipitation is likely in the south-western districts, while the other districts have insignificant increases in monthly precipitation under SSP1 2.6. Under SSP2 4.5 the northern and part of central districts are likely to experience a higher increase in precipitation than the southern districts. July, August, and September might see decreased precipitation in the south-eastern districts (*Figure 15 and Figure 16*).

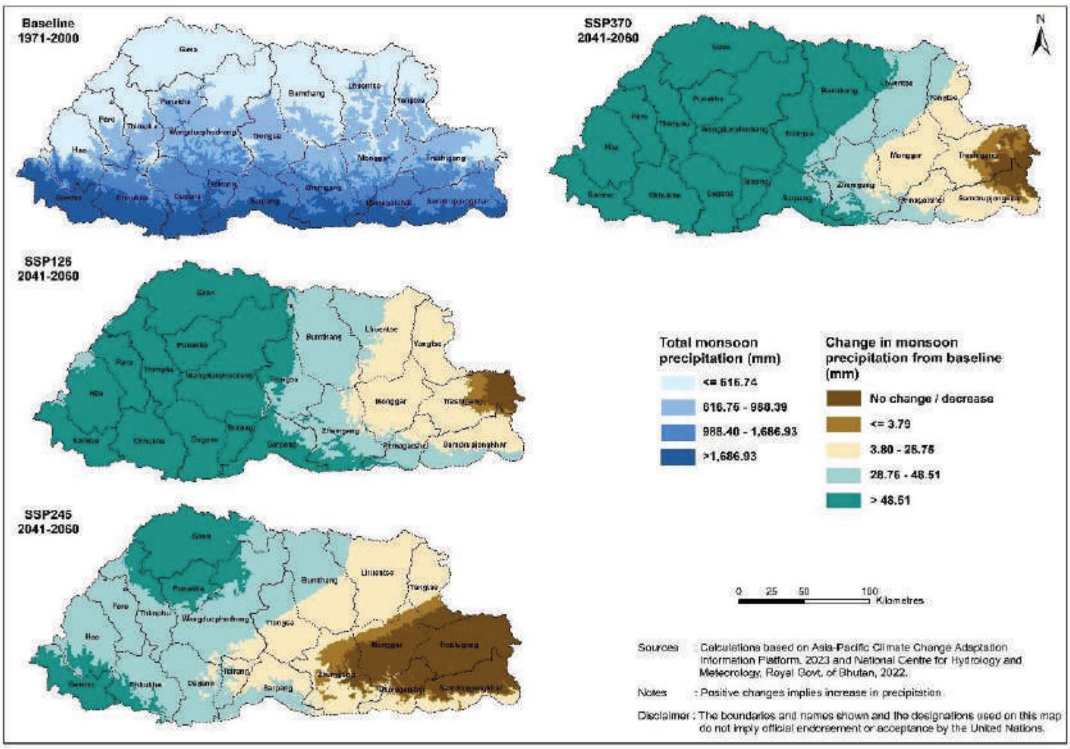
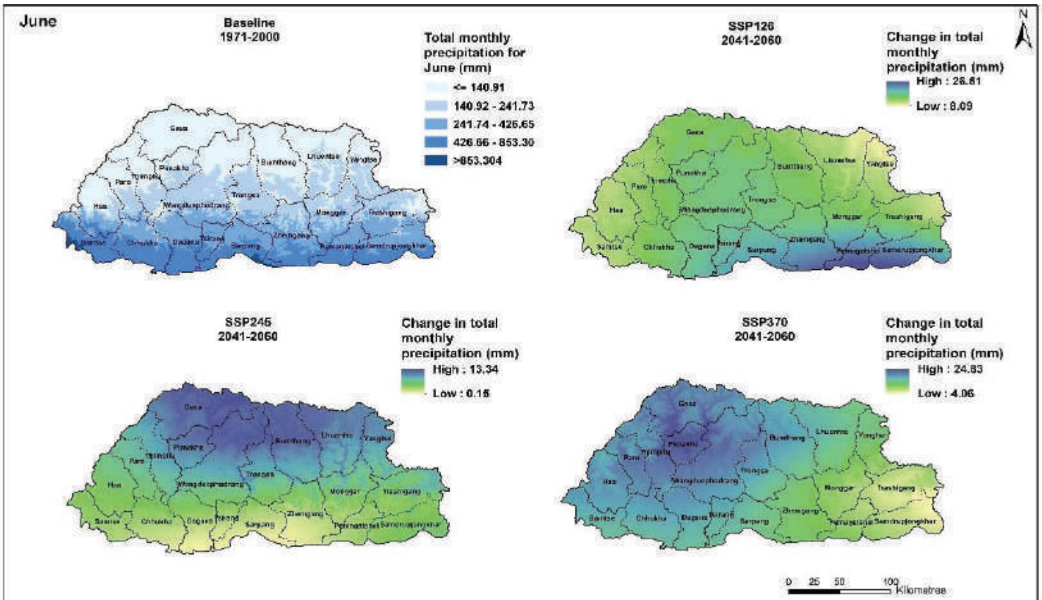


Figure 15 Total monsoon precipitation under baseline scenario and change in total monsoon precipitation from baseline under SSP1 2.6, SSP2 4.5 and SSP3 7.0 scenario by 2060



Sources : Calculations based on Asia-Pacific Climate Change Adaptation Information Platform, 2023 and National Centre for Hydrology and Meteorology, Royal Govt. of Bhutan, 2022.

Notes : Positive changes implies increase in precipitation and negative implies decrease in precipitation.

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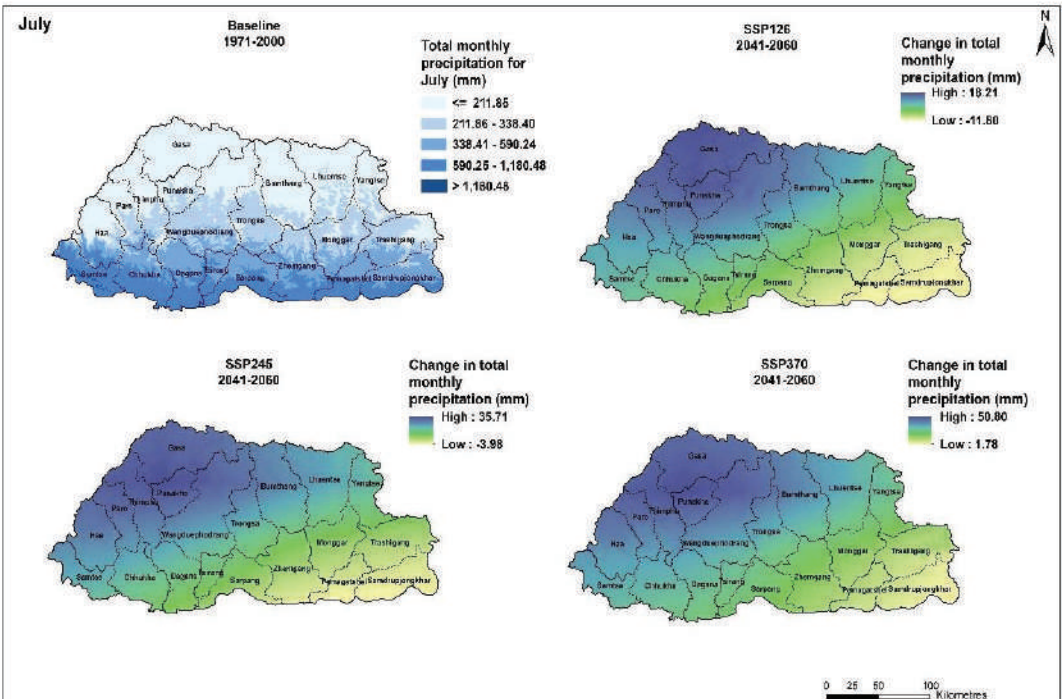

Sources : Calculations based on Asia-Pacific Climate Change Adaptation Information Platform, 2023 and National Centre for Hydrology and Meteorology, Royal Govt. of Bhutan, 2022.

Notes : Positive changes implies increase in precipitation and negative implies decrease in precipitation.

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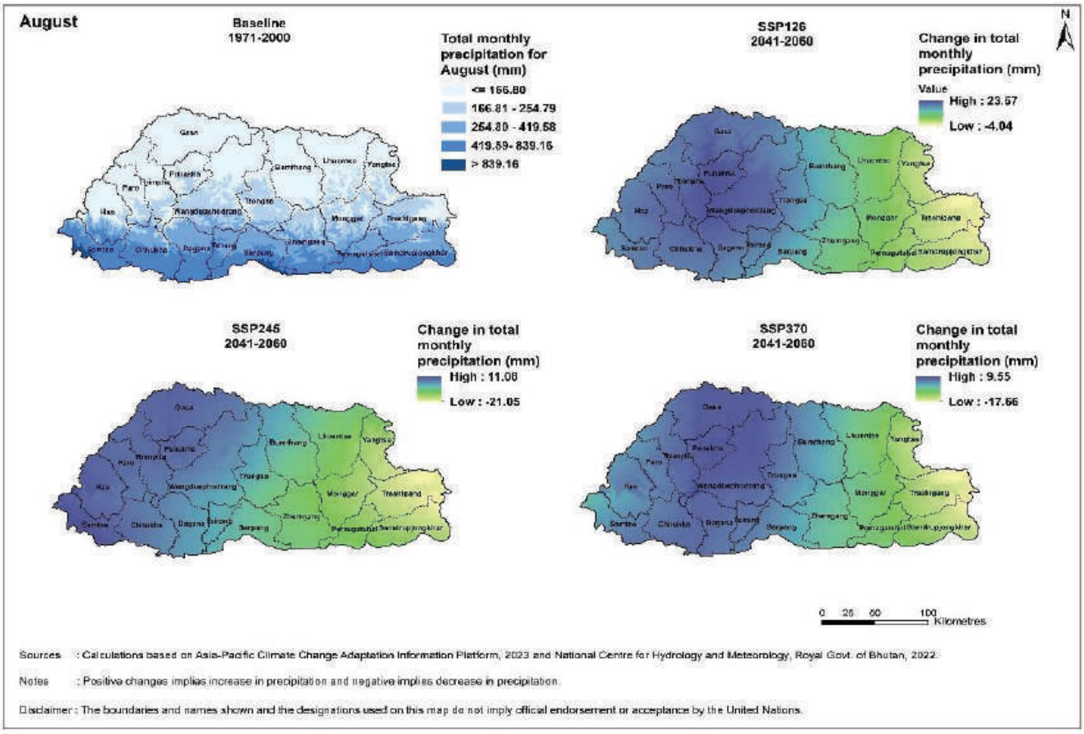


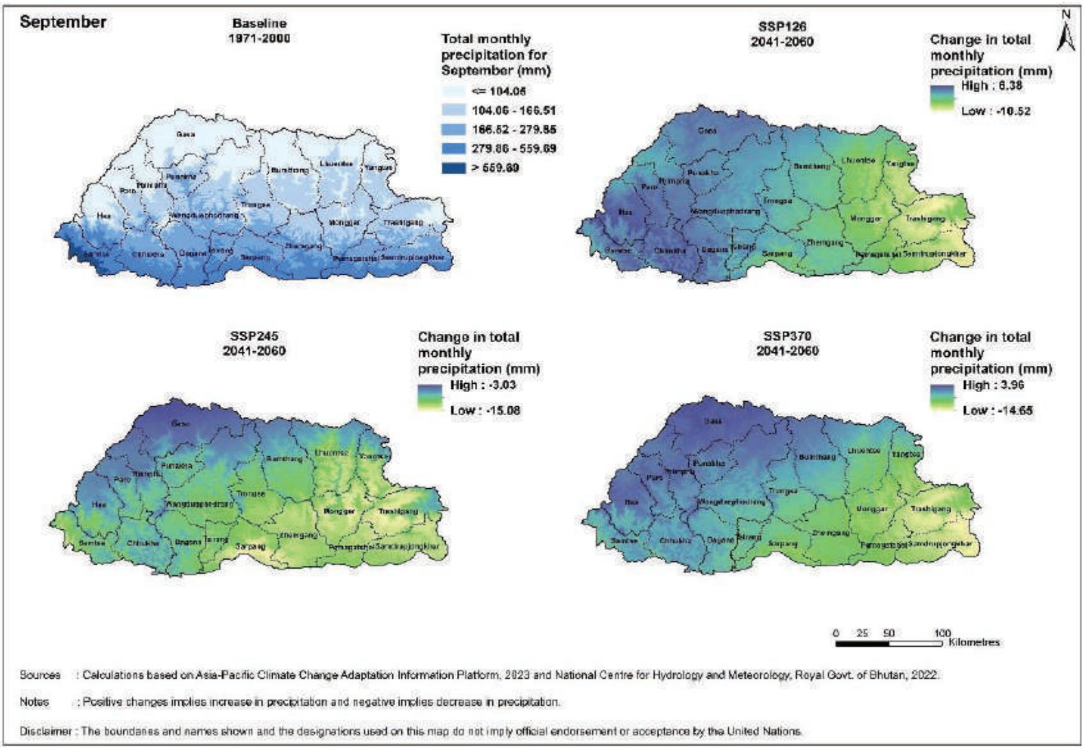


Figure 16 Total precipitation for June, July, August September under baseline scenario and change in total precipitation for September from baseline under SSP1 2.6, SSP2 4.5 and SSP3 7.0 scenario by 2060

Winter precipitation by 2060

By 2060, all the districts of Bhutan are likely to receive more precipitation than baseline under all climate change scenarios, however the increase is less under SSP3 7.0 than the other two scenarios. More increase is likely from the central to the southern districts. Zhemgang, Sarpang, Pema Gatshel and Samdrup Jongkhar are likely to experience the highest increase in precipitation in the dry season by up to 66mm with SSP1 2.6, 65mm with SSP2 4.5 and 44mm with SSP3 7.0 scenario (Figure 17).

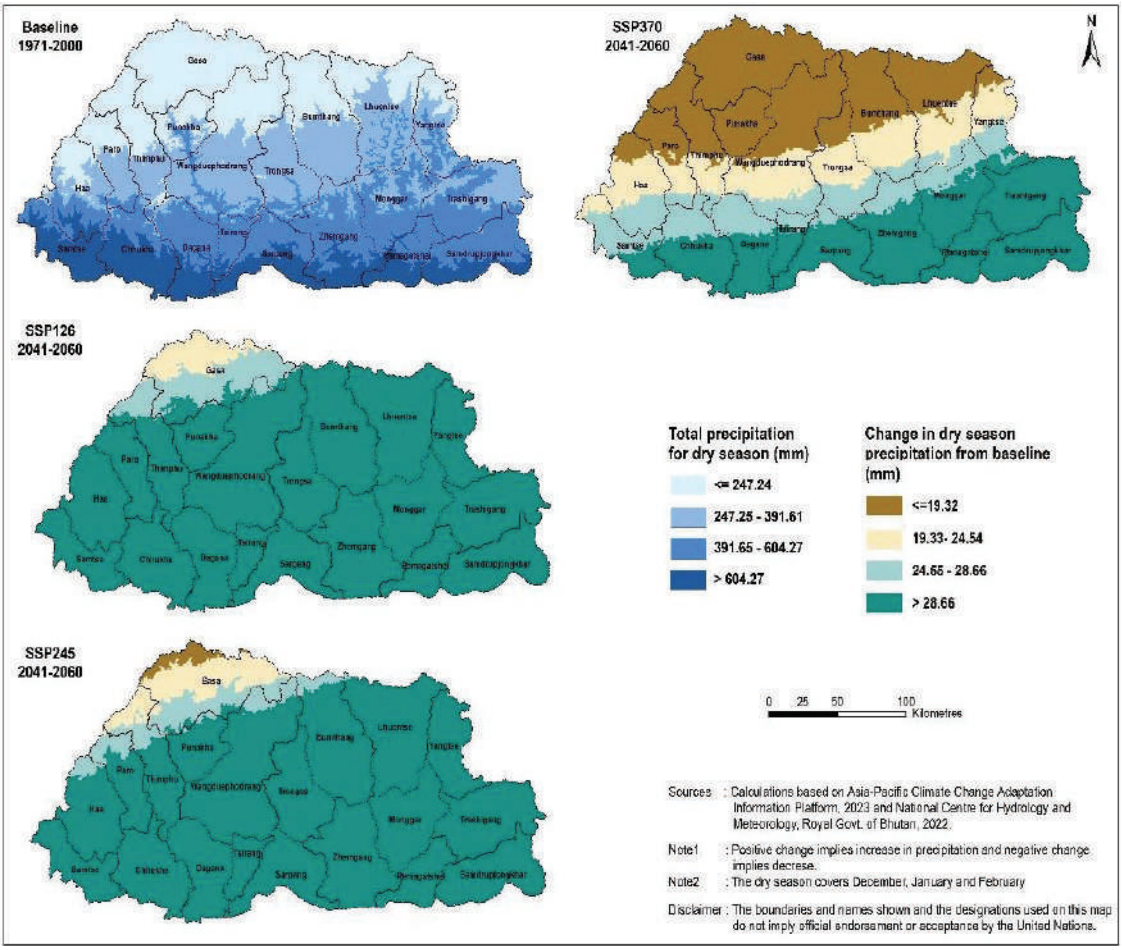


Figure 17 Total precipitation for the dry season under baseline scenario and change in total monsoon precipitation from baseline under SSP1 2.6, SSP2 4.5 and SSP3 7.0 scenario by 2060

Monsoon precipitation by 2100

By the end of the century, all the districts are likely to receive more precipitation from baseline. The maximum increase in precipitation may range between 130 mm (SSP1 2.6) to 327 mm (SSP3 7.0). The top 5 districts with the expected highest increase in precipitation are Trongsa, Samtse, Tsirang, Wangdue Phodrang, and Dagana. Paro and Thimphu are likely to experience around 300mm increase in precipitation under the worst-case scenario. Among the monsoon months, July is likely to see the highest increase in precipitation concentrated mainly in the north-west and south-western districts and the distribution pattern follows the seasonal one (Figure 18 and Figure 19).

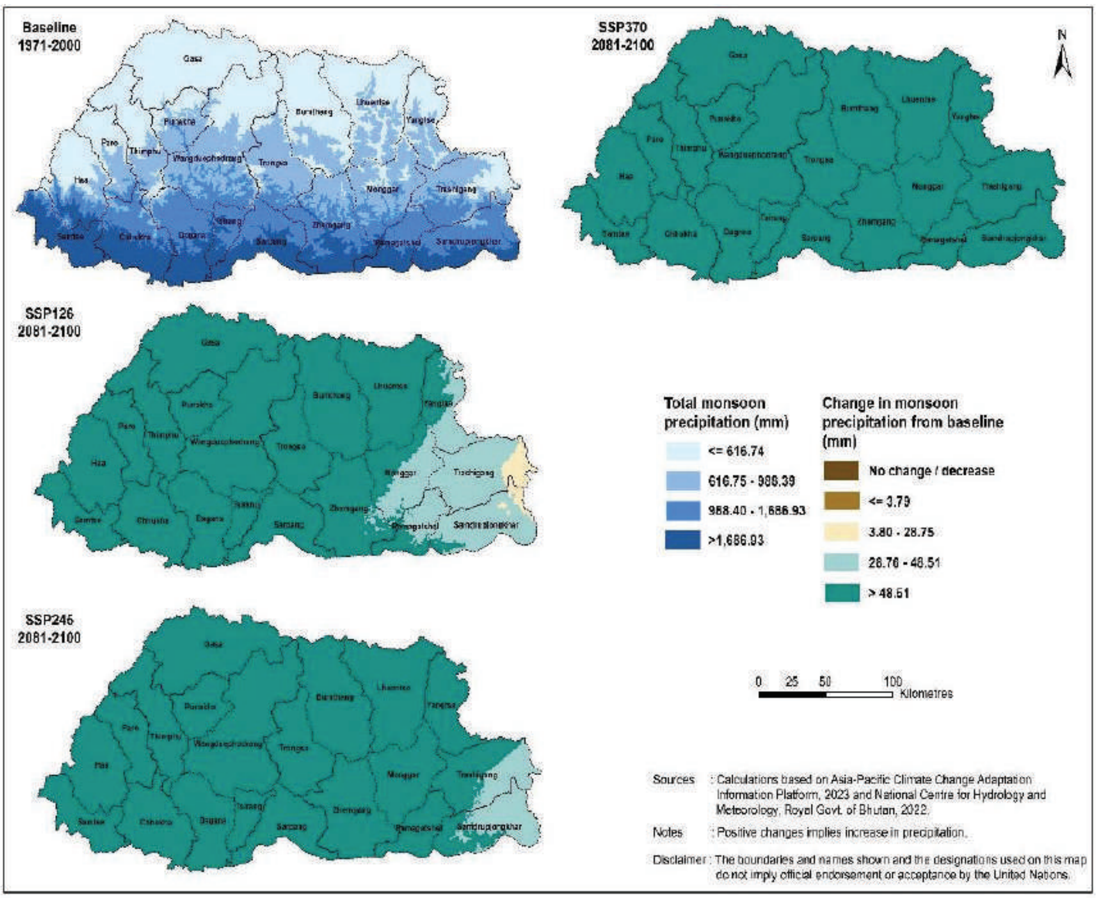
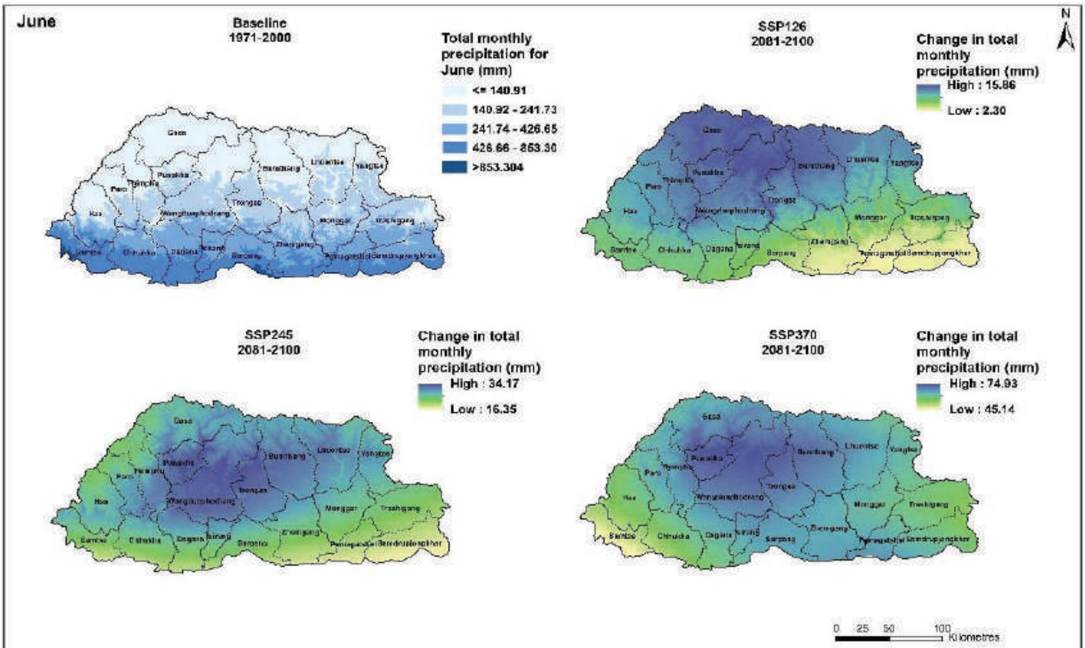


Figure 18 Total monsoon precipitation under baseline scenario and, change in total monsoon precipitation from baseline under SSP1 2.6, SSP2 4.5 and SSP3 7.0 scenario by 2100



Sources : Calculations based on Asia-Pacific Climate Change Adaptation Information Platform, 2023 and National Centre for Hydrology and Meteorology, Royal Govt. of Bhutan, 2022.

Notes : Positive changes implies increase in precipitation and negative implies decrease in precipitation.

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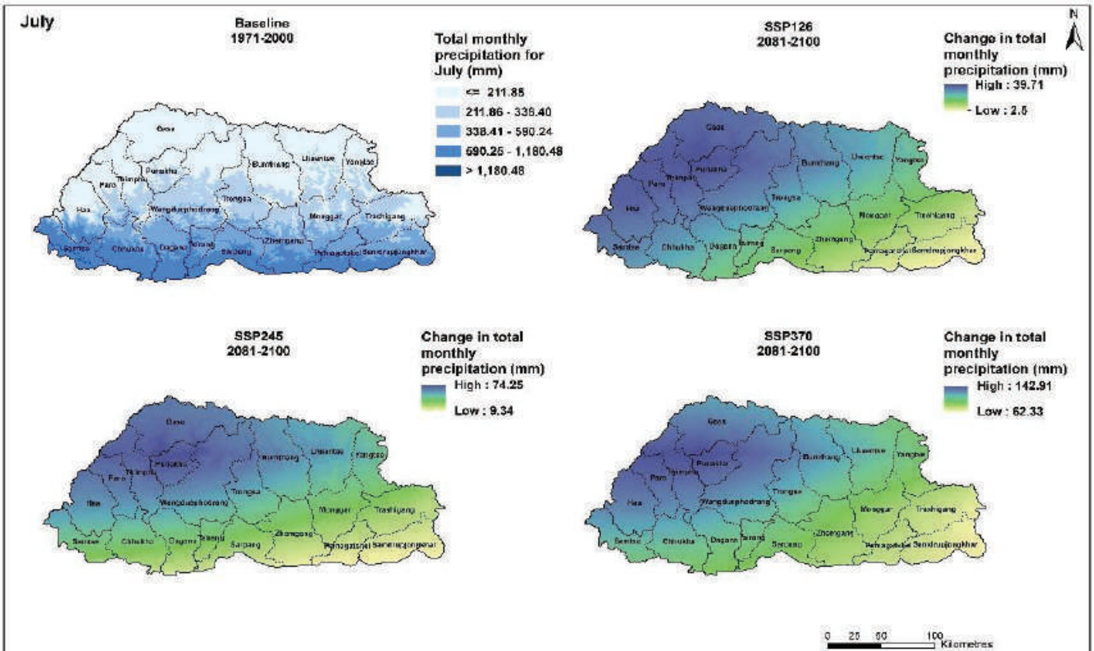

Sources : Calculations based on Asia-Pacific Climate Change Adaptation Information Platform, 2023 and National Centre for Hydrology and Meteorology, Royal Govt. of Bhutan, 2022.

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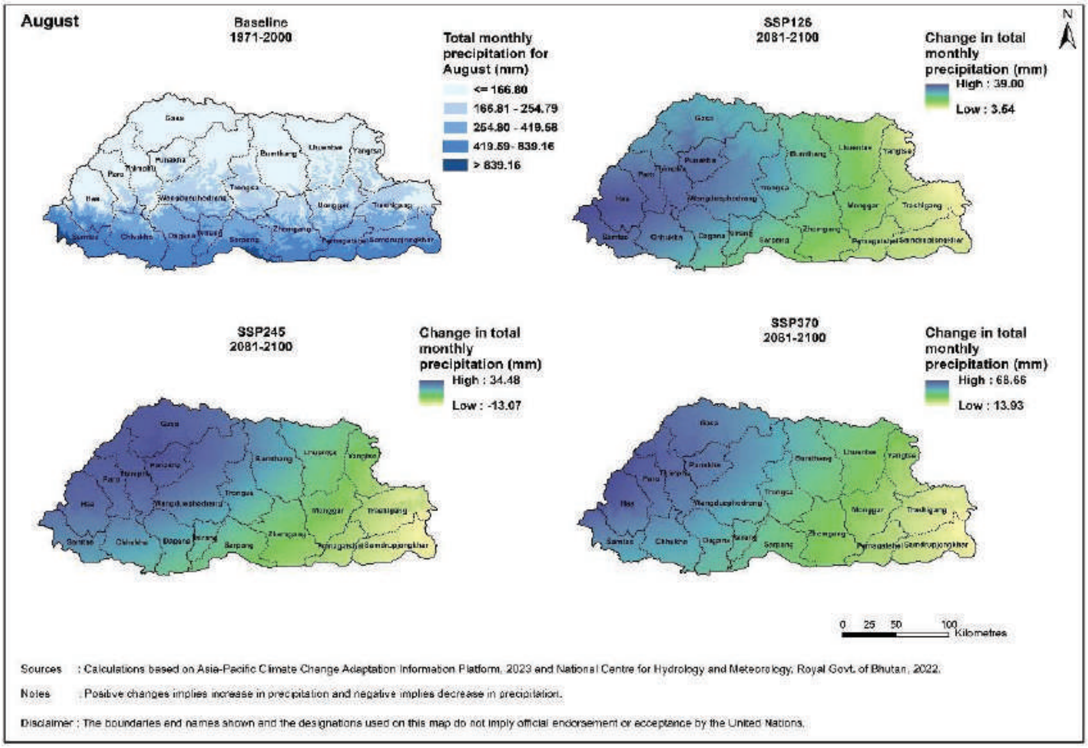

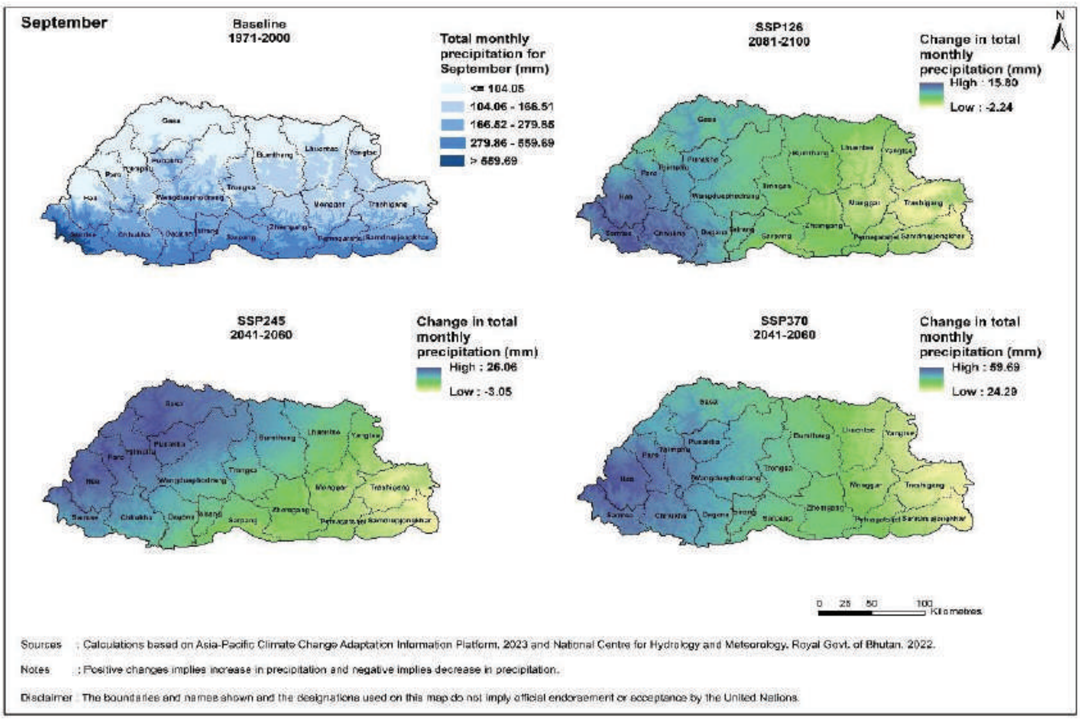

Figure 19 Total precipitation for June, July, August September under baseline scenario and change in total precipitation for June, July, August and September from baseline under SSP1 2.6, SSP2 4.5 and SSP3 7.0 scenario by 2100

Winter precipitation by 2100

The precipitation in the dry season by 2100 is similar to 2060. But, with SSP1 2.6 scenario the increase in precipitation in the northern and north-western districts are likely to be less compared to that in 2060. Zhemgang, Sarpang, Pema Gatshel, Trashigang, Trashi Yangtse and Samdrup Jongkhar are likely to experience the highest increase in precipitation by up to 42mm with SSP1 2.6, 76mm with SSP2 4.5 and 154mm with SSP3 7.0 scenario (Figure 20).

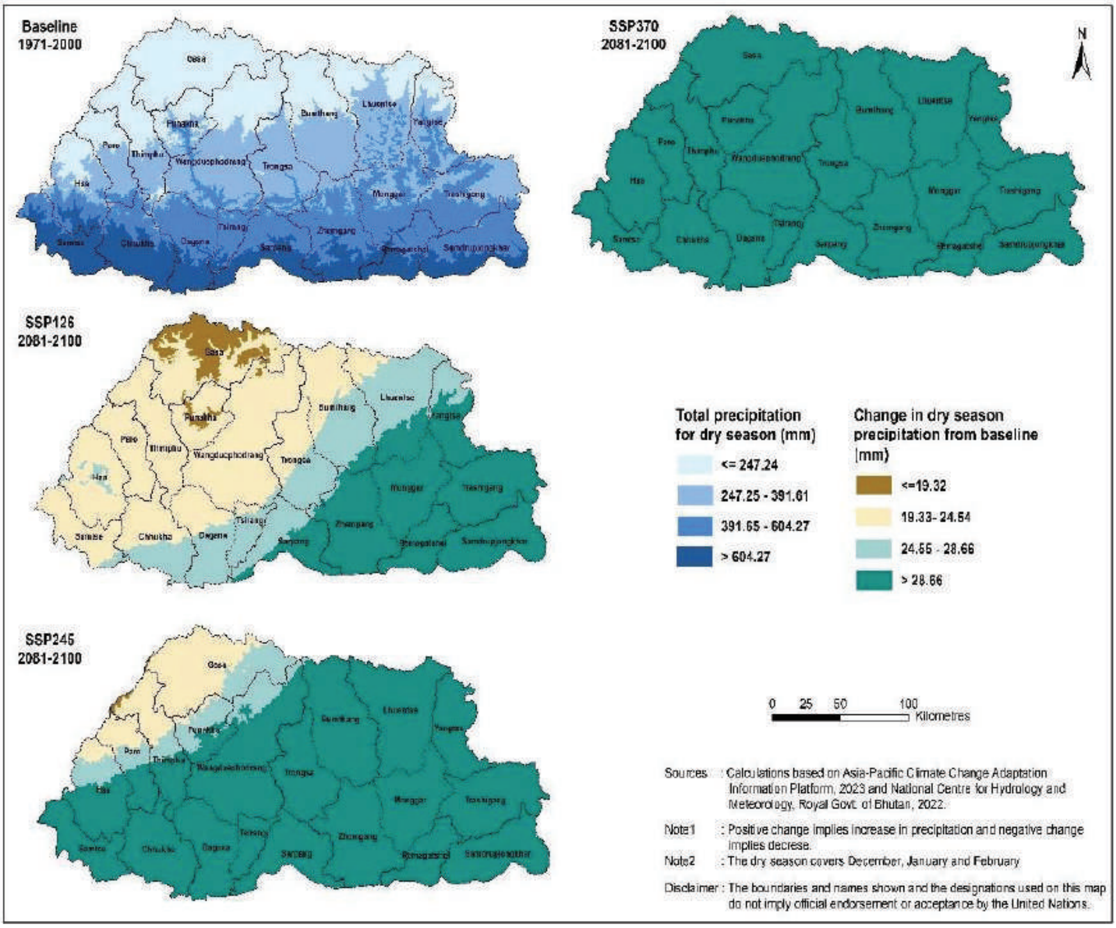

Figure 20 Total precipitation for the dry season under baseline scenario and change in total monsoon precipitation from baseline under SSP1 2.6, SSP2 4.5 and SSP3 7.0 scenario by 2100

4.2 Temperature

4 .2.1 Annual temperature

In Bhutan, temperature varies widely due to the dramatic variation in the elevation. In general, temperatures are higher in the southern part of the country and decreases northwards. IPCC AR6 has highlighted that elevation dependent warming is likely to continue in the mountain regions in Asia under the climate change conditions[15]. Additionally, the rate of warming might be amplified with elevation, for example, the high-mountain environments may experience faster changes in temperature than that at lower elevations[16]. Under climate change scenarios the trend remains the same, however the northern part is likely to experience more increase in temperature than the southern part. Figure 22 demonstrates the changes in average annual maximum (Tmax) and minimum temperature (Tmin) under three different climate change scenarios by 2040. Across all the scenarios both the minimum and maximum temperature increases more in the northern districts in the high mountain regions than the districts in the foothill region in the south. The maximum increase in Tmax may reach up to 1.55 °C (Gasa) while Tmin up to 1.9°C (Gasa) under the worst-case. scenario by 2040. In Bumthang, Wangdue Phodrang, Lhuentse, Thimphu, Punakha, Paro and Trongsa the Tmax is likely to increase by more than 1.4°C and Tmin by more than 1.7°C under the worst-case scenario by 2040 (*Figure 22, Figure 23*).

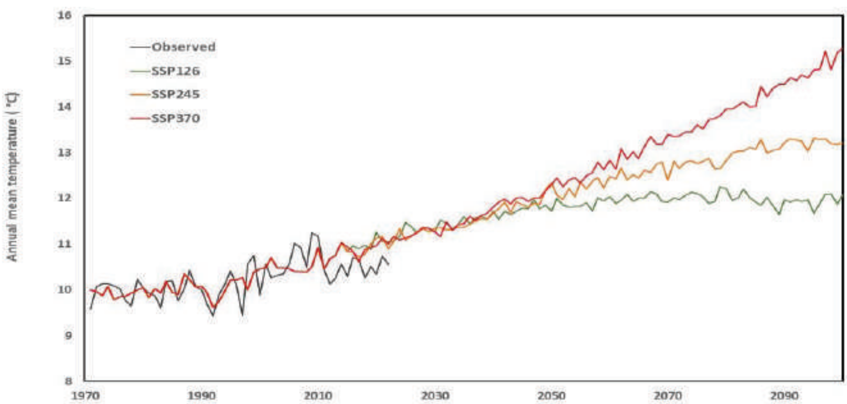

Figure 21 Annual mean temperature projection for three different scenarios (ensemble)

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[15] https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_Chapter10.pdf

[16] Mountain Research Initiative EDW Working Group. Elevation-dependent warming in mountain regions of the world. *Nature Clim Change* **5**, 424–430 (2015). https://doi.org/10.1038/nclimate2563 available at https://www.nature.com/articles/nclimate2563

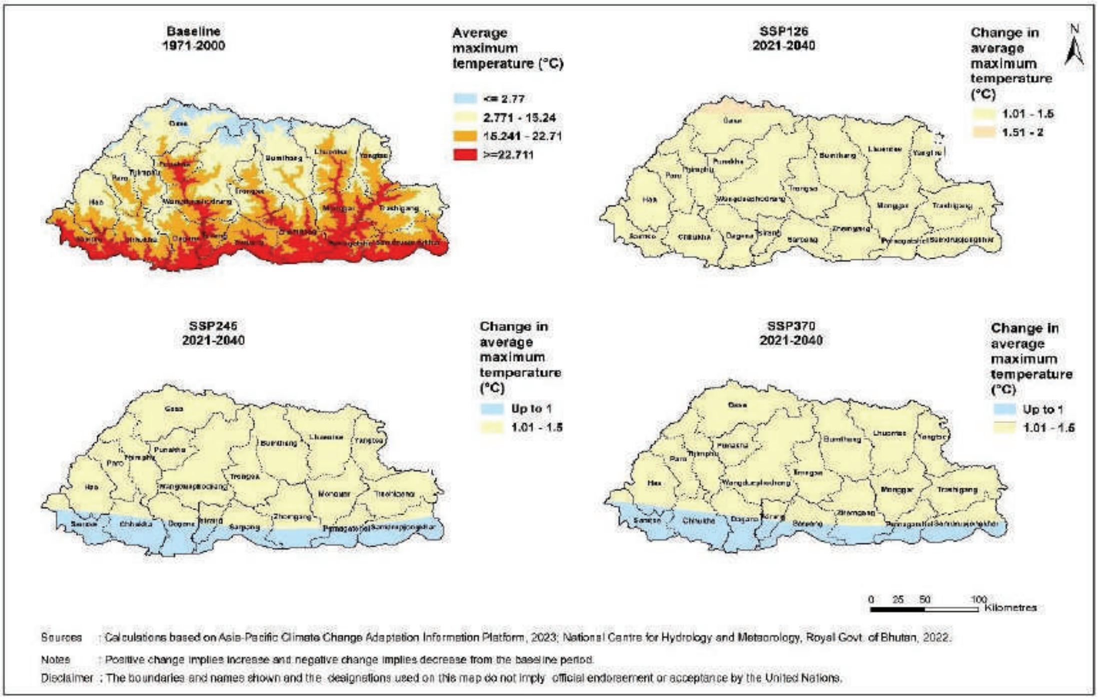


Figure 22 Average annual maximum temperature and change in average annual maximum temperature from baseline under SSP1 2.6, SSP2 4.5 and SSP3 7.0 scenario by 2040

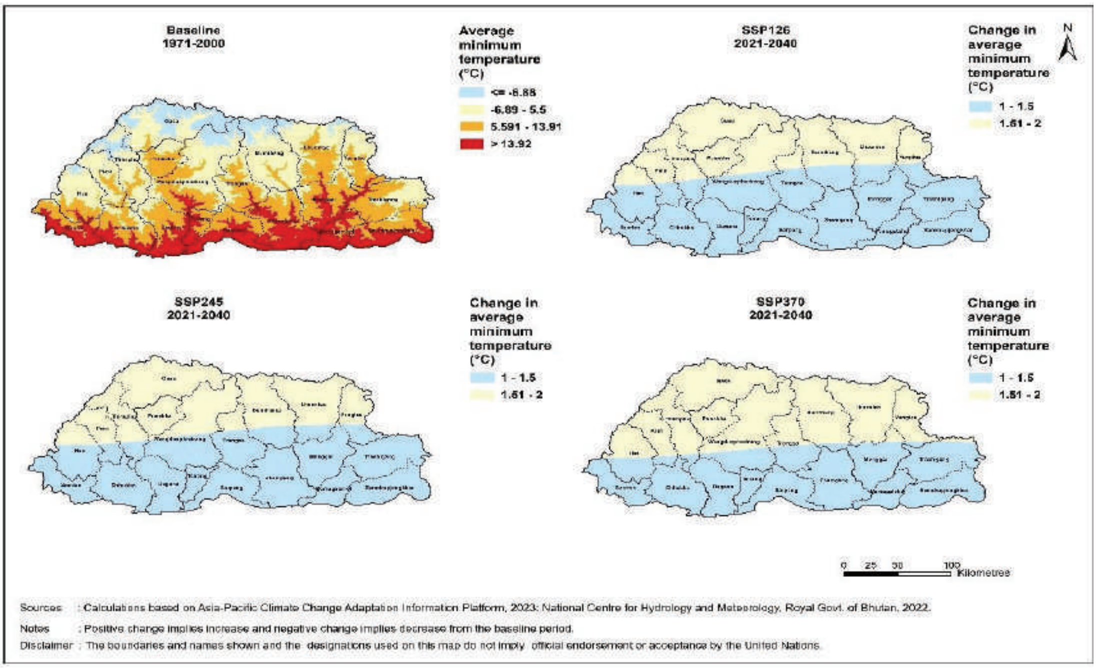


Figure 23 Average annual minimum temperature change in average annual minimum temperature from baseline under SSP1 2.6, SSP2 4.5 and SSP3 7.0 scenario by 2040 in Bhutan

By 2060, the maximum and minimum temperatures are likely to further increase, more in the northern districts. Maximum increase in Tmax is likely in Gasa where it ranges between 1.9°C (SSP1 2.6) to 2.5°C (SSP3 7.0). In Bumthang, Wangdue Phodrang, Lhuentse, Thimphu, Punakha, Paro and Trongsa Tmax may increase between 1.8°C (SSP1 2.6) to 2.3°C (SSP3 7.0). The increase in Tmin is more than Tmax across the country. The Maximum increase is likely in Gasa where it ranges between 2.3 °C (SSP1 2.6) to 3.1 °C (SSP3 7.0). Bumthang, Wangdue Phodrang, Lhuentse, Thimphu, Punakha, Paro and Trongsa increase in Tmin might range between 2°C (SSP1 2.6) to 2.8°C (SSP3 7.0) by 2060 (Figure 24, figure 25).

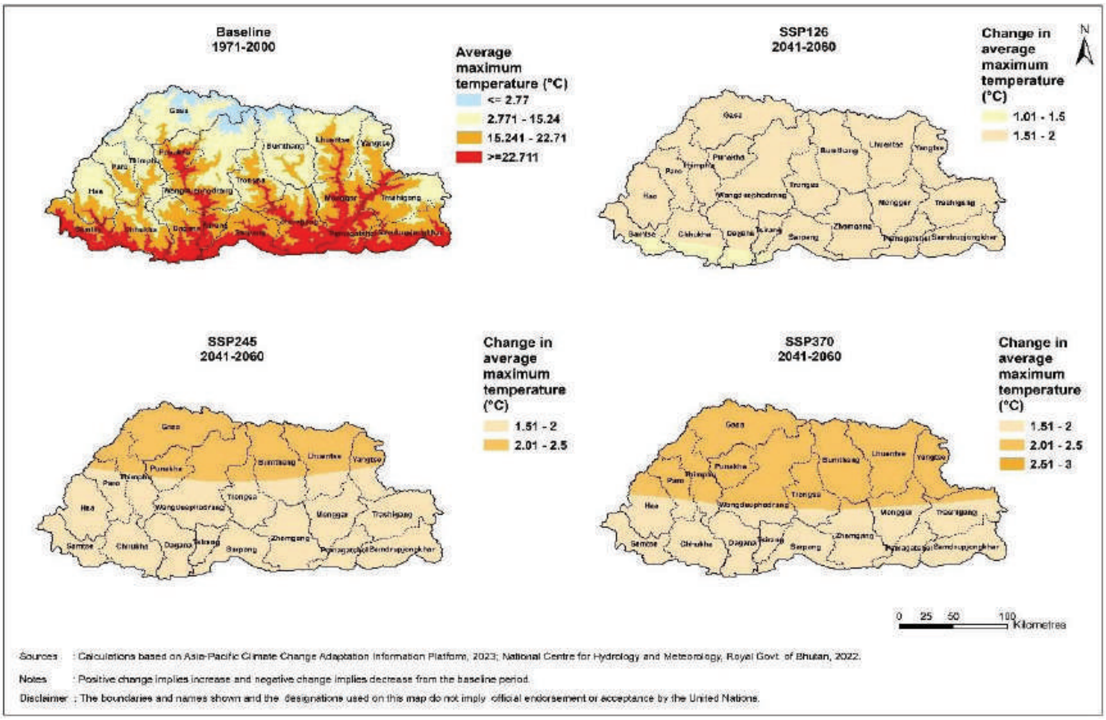


Figure 24 Average annual maximum temperature and change in average annual maximum temperature from baseline under SSP1 2.6, SSP2 4.5 and SSP3 7.0 scenario by 2060

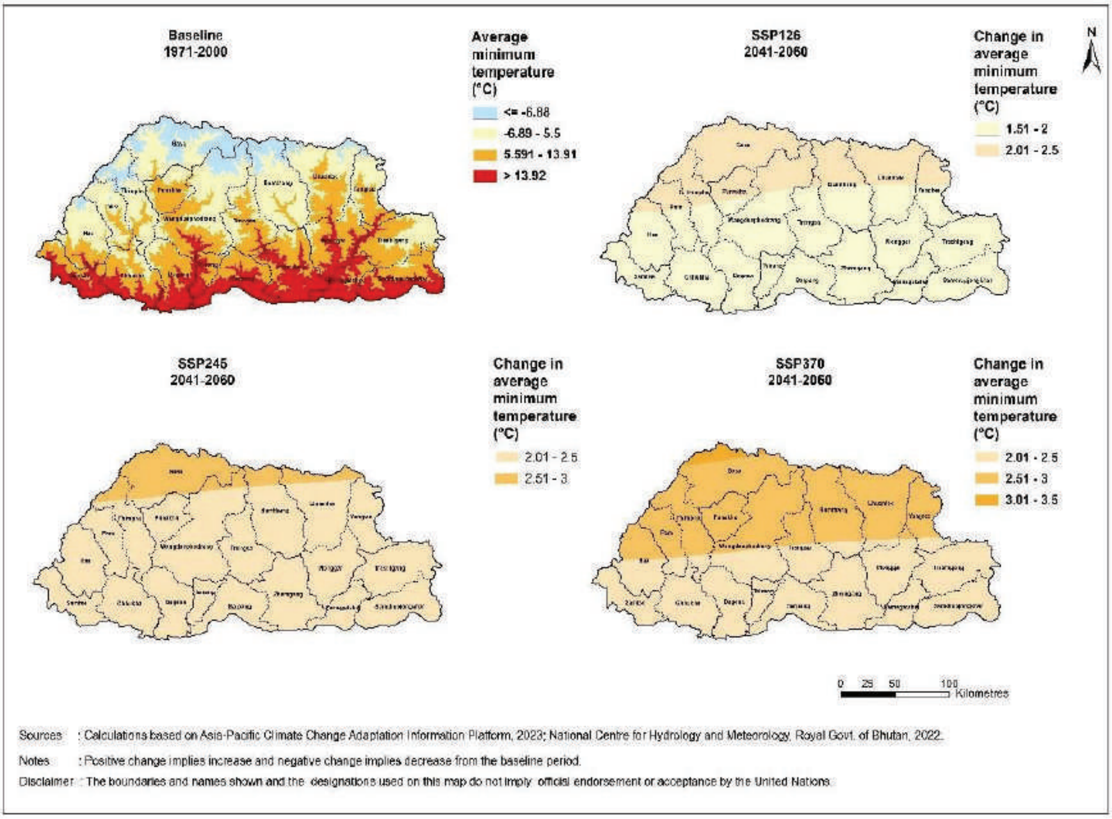


Figure 25 Average annual minimum temperature change in average annual minimum temperature from baseline under SSP1 2.6, SSP2 4.5 and SSP3 7.0 scenario by 2060

By 2100, the maximum increase in Tmin is likely in Gasa where the rise in Tmin may reach up to 2.3°C under SSP1 2.6 and may go beyond 5°C under SSP3 7.0. The rise in Tmin in other districts such as Bumthang, Wangdue Phodrang, Lhuentse, Thimphu, Punakha, Paro and Trongsa Tmin may also go beyond 5°C under SSP3 7.0 by 2100, however in best-case scenario it is likely to reach just above 2°C. Likewise the highest increase in Tmax may range between 2.1°C to around 5°C (Gasa) followed by Bumthang, Wangdue Phodrang, Lhuentse, Thimphu, Punakha, Paro and Trongsa where increase in Tmax may reach more than 4°C (Figure 26, Figure 27)

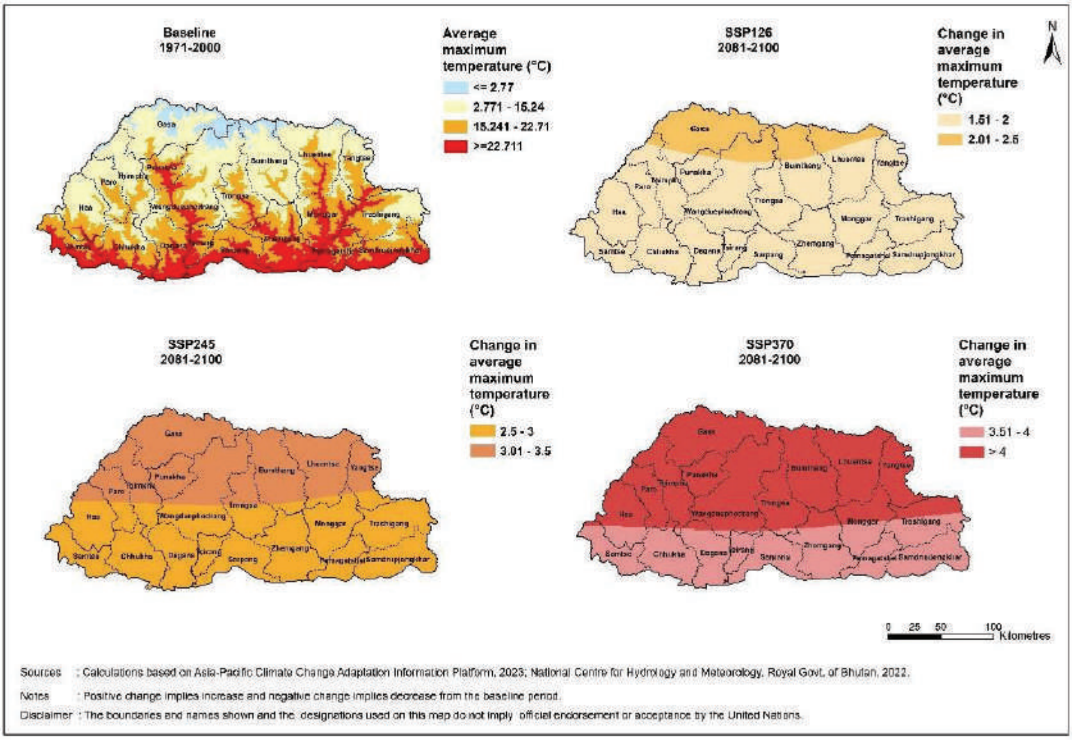


Figure 26 Average annual maximum temperature and change in average annual maximum temperature from baseline under SSP1 2.6, SSP2 4.5 and SSP3 7.0 scenario by 2100 in Bhutan

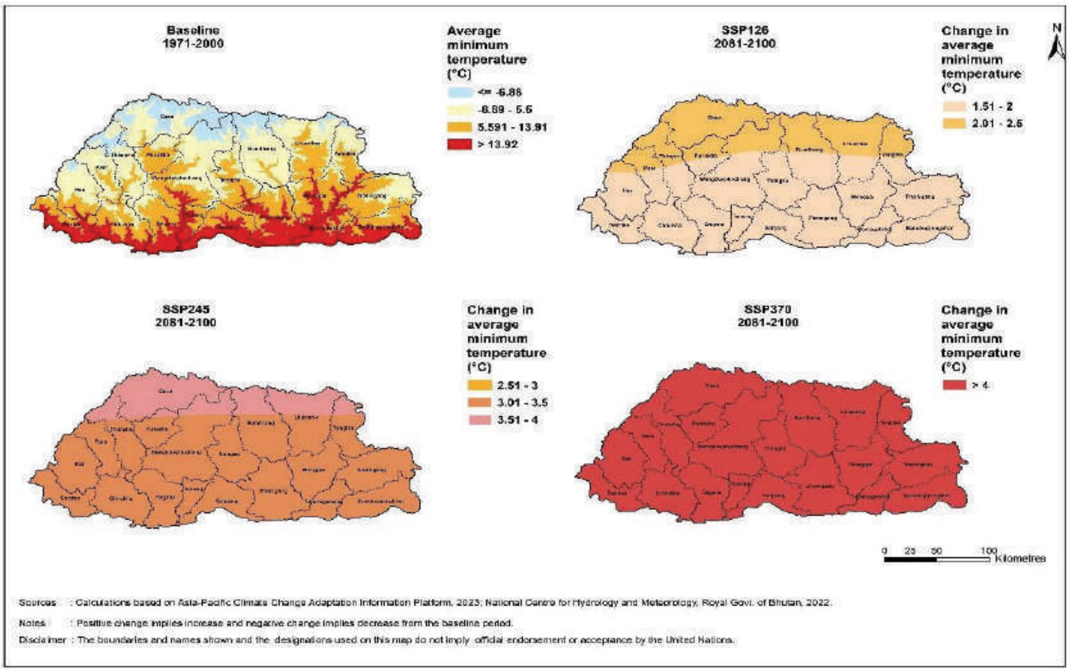


Figure 27 Average annual minimum temperature change in average annual minimum temperature from baseline under SSP1 2.6, SSP2 4.5 and SSP3 7.0 scenario by 2100 in Bhutan

4.2.2 Summer and winter temperature

The summer season in Bhutan coincides with the monsoon months i.e. June to September. Although the summer Tmax is likely to increase across the country under all climate change scenarios the increase is more in the central to northern districts than southern districts. The high mountain glaciers are located in the northern part of Gasa, Bumthang, Wangdue Phodrang, Lhuentse, Thimphu and Haa districts. An increase in summer temperature in those districts may lead to more melting of glaciers in the summer.

Again By 2040, the summer temperature is likely to increase by up to 1.3°C in these districts under the worst-case scenario (Figure 28). In the mid-term (by 2060) the Tmax may rise by 1.8°C under SSP1 2.6 and by just over 2°C under SSP3 7.0 in these districts (Figure 18). In the long-term, by 2100, increase in Tmax may reach up to 4°C under SSP3 7.0 while it may remain around 1.9°C under SSP1 2.6 climate change scenario (Figure 26). On the other hand, as the summer Tmax is already higher in the southern districts such as Samtse, Chhukha, Dagana, Sarpang, Tsirang, Zhemgang, Pema Gatshel and Samdrup Jongkhar. Further increase may lead to the risk of heatwave. By 2040, Tmax can rise by just over 1°C in these districts across all the scenarios (Figure 17). During the mid-term period, summer Tmax is likely to increase by 1.3°C to 1.7°C under SSP1 2.6 and SSP 3 7.0 respectively in these districts (Figure 18). By 2100, summer increase in Tmax may range from 1.6 under SSP1 2.6 to around 3.5°C under SSP3 7.0 (Figure 27)

The spatial distribution of winter minimum temperature (for December, January and February) for the baseline follows the same pattern as the summer temperature. It decreases as we move towards the north. Under the climate change scenarios, the winter temperature is likely to increase more in the northern districts by 2040. The highest increase in average minimum temperature in the winter months is likely in Lhuentse (> 2 °C) across all the scenarios. More than 1.9°C increase is likely in Punakha, Wangdu Phodrang, Paro, Thimphu, Gasa, Bumthang, Trashi Yangtse and Lhuentse by 2040 under all the scenarios (Figure 25). In the mid-term (by 2060) the increase average minimum temperature in the winter may reach up to 3.4°C with SSP3 7.0. In winter under SSP1 2.6 all the districts are likely to experience more than 2°C increase in the minimum temperature except Sarpang and Tsirang where it will remain around 1.9°C, whereas Lhuentse might experience an increase of about 2.5°C. Under SSP2 4.5 all the districts are likely to have 2.38°C or more increase in minimum temperature while

Lhuentse and Trashi Yangtse may have more than 3°C increase. Under SSP3 7.0 Monggar, Trongsa Punakha, Wangdue Phodrang, Paro, Thimphu, Gasa, Bumthang, Trashi Trashi Yangtse and Lhuentse might see increase of minimum temperature more than 3°C (Figure 26).

By 2100, all the districts are likely to experience at least 2°C increase in minimum temperature in the winter months under SSP1 2.6 and SSP3 7.0 while SSP2 4.5 it is 1.55°C. In the case of SSP3 7.0, all the districts are likely to have at least 4.9°C increase in average minimum temperature. Lhuentse have the likelihood of experiencing the highest increase under SSP1 2.6 (2.55°C) and SSP2 4.5 (2.03 °C) scenarios, whereas under SSP3 7.0 Gasa tops the list with 6.49°C (Figure 27).

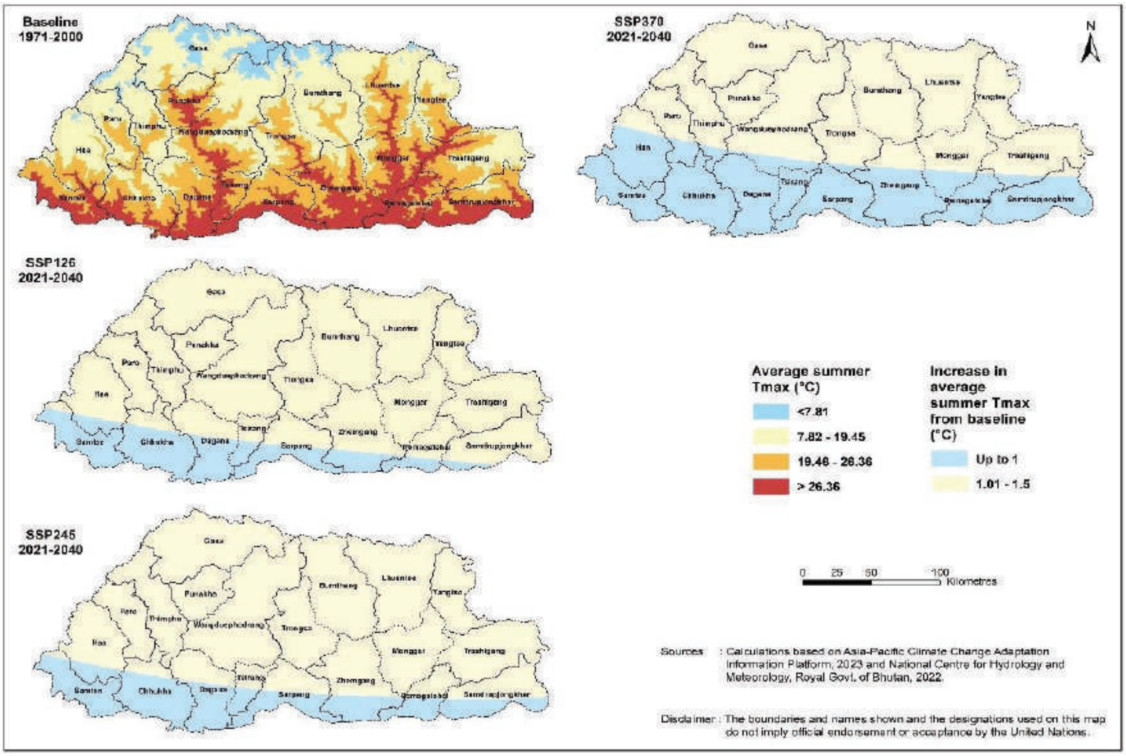


Figure 28 Average maximum summer temperature under baseline scenario and change in average maximum summer temperature from baseline under SSP1 2.6, SSP2 4.5 and SSP3 7.0 scenario by 2040

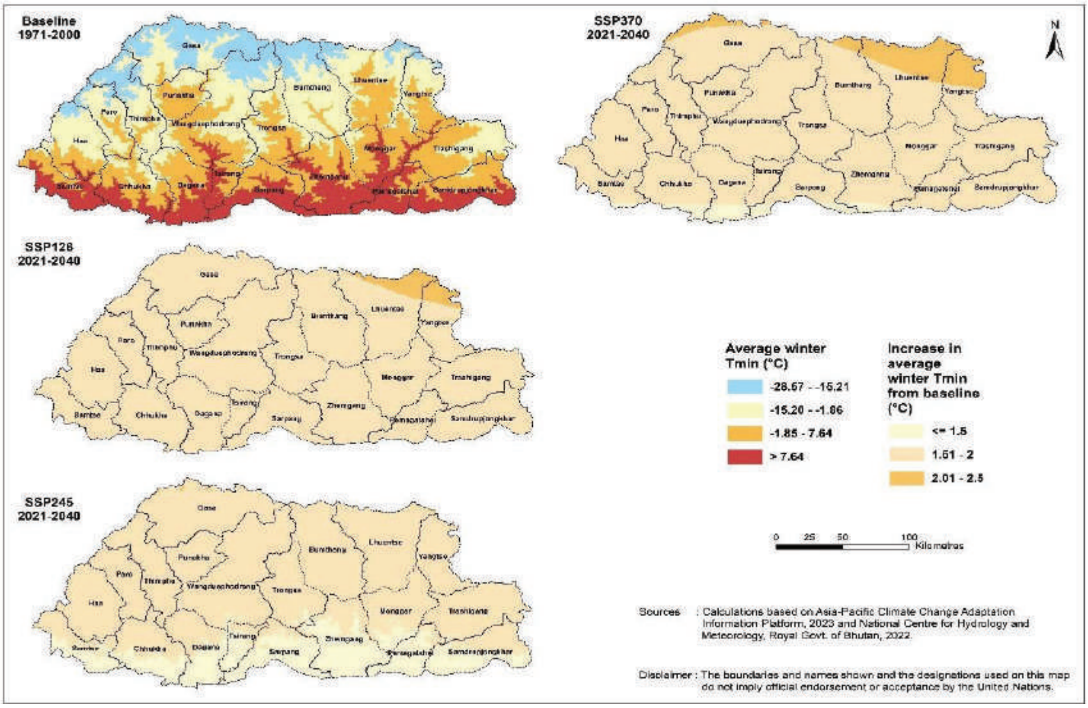


Figure 29 Average minimum winter temperature and change in average minimum winter temperature from baseline under SSP1 2.6, SSP2 4.5 and SSP3 7.0 scenario by 2040

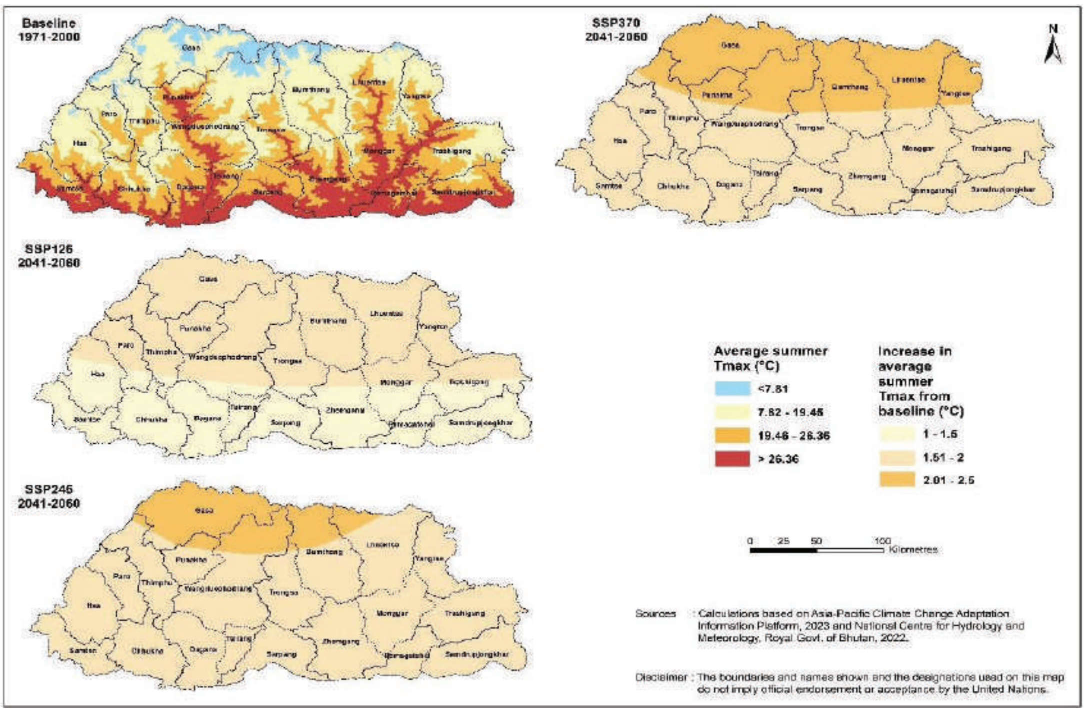


Figure 30 Average maximum summer temperature under baseline scenario and change in average maximum summer temperature from baseline (top) under SSP1 2.6, SSP2 4.5 and SSP3 7.0 scenario by 2060

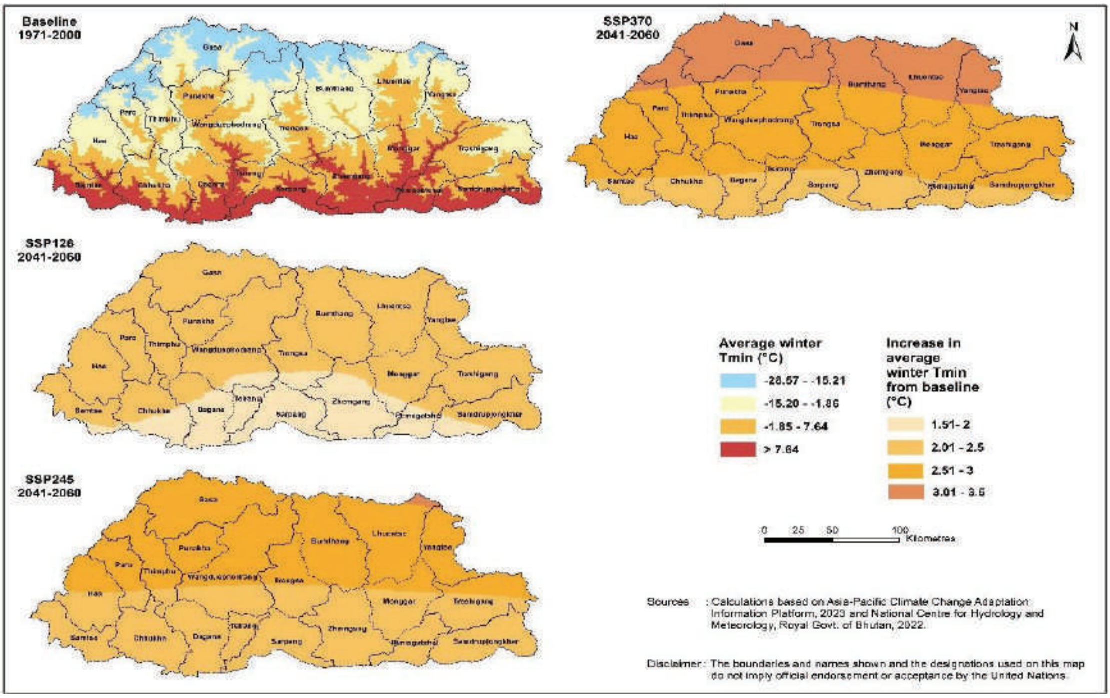


Figure 31 Average minimum winter temperature and change in average minimum winter temperature from baseline under SSP1 2.6, SSP2 4.5 and SSP3 7.0 scenario by 2060

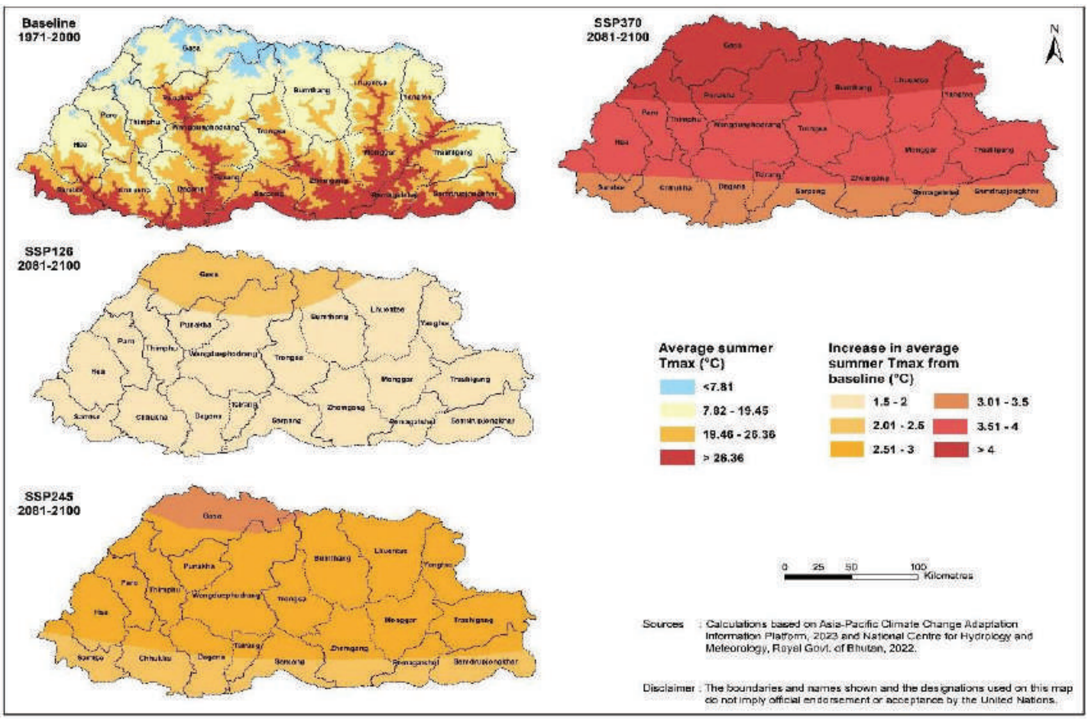


Figure 32 Average maximum summer temperature under baseline scenario and change in average maximum summer temperature from baseline under SSP1 2.6, SSP2 4.5 and SSP3 7.0 scenario by 2100

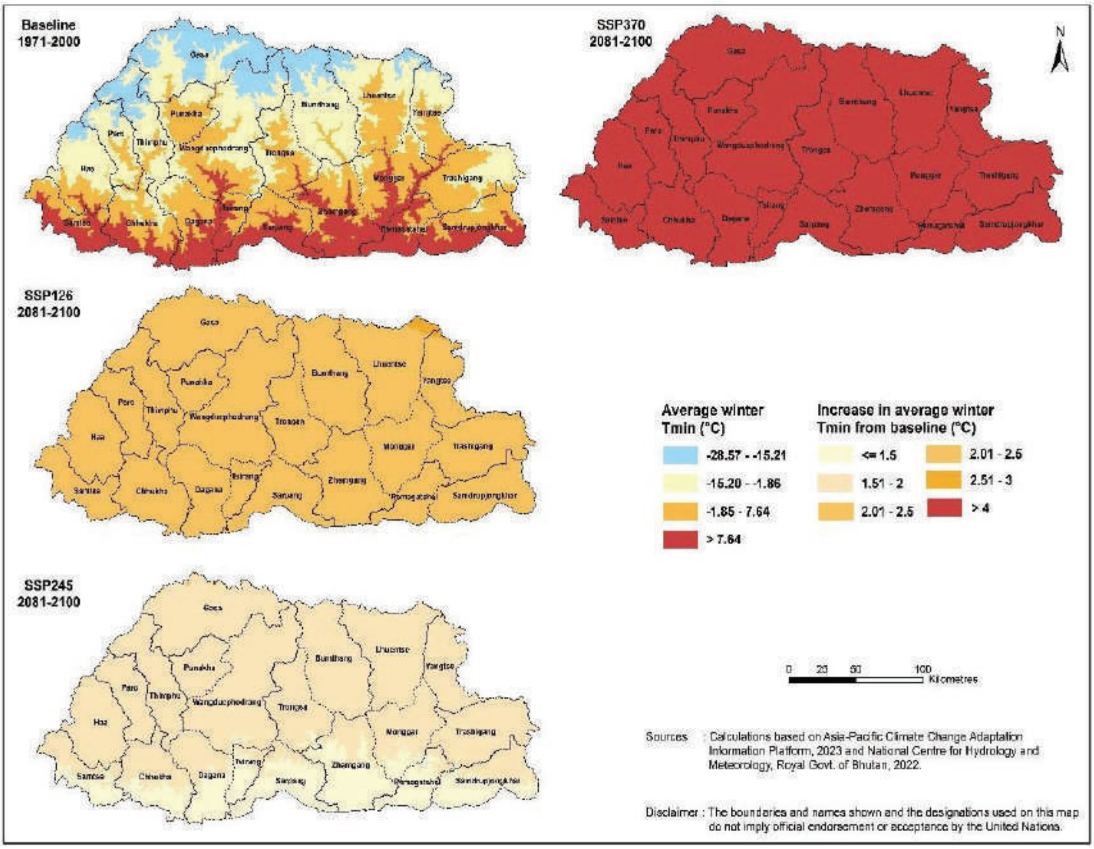


Figure 33 Average minimum winter temperature and change in average minimum winter temperature from baseline under SSP1 2.6, SSP2 4.5 and SSP3 7.0 scenario by 2100

4.3 Glacier mass balance and runoff

4.3.1 Glacier mass balance

"The mass balance of a glacier is the sum of all processes that add mass to a glacier and remove mass from it."[17] If the mass balance is nearly 0, that means the glacier has a mass balance that is in equilibrium with the climate, and it does not retreat or advance. The negative mass balance indicates more melting in glaciers than accumulation, while positive mass balance indicates more accumulation than melt. Glaciers with negative mass balance will shrink and vice-versa.

[17] https://link.springer.com/referenceworkentry/10.1007/978-90-481-2642-2_341

By 2040 the total mass balance of the glaciers is likely to be most negative in the Wang Chhu basin, but some of the glaciers in Manas Chhu and Punatsang Chhu are likely to have high negative mass balance, especially under RCP8.5 (Figure 34).

During mid-term (2041-2060) and long-term (2081-2100) most of the glaciers in the Manas Chhu and Punatsang Chhu basin may be negative with some located around the northern border having positive total mass balance under SSP 2.6 and SSP4.5. However, most of them are likely to have negative mass balance under SSP8.5 (Figure 35; Figure 36).

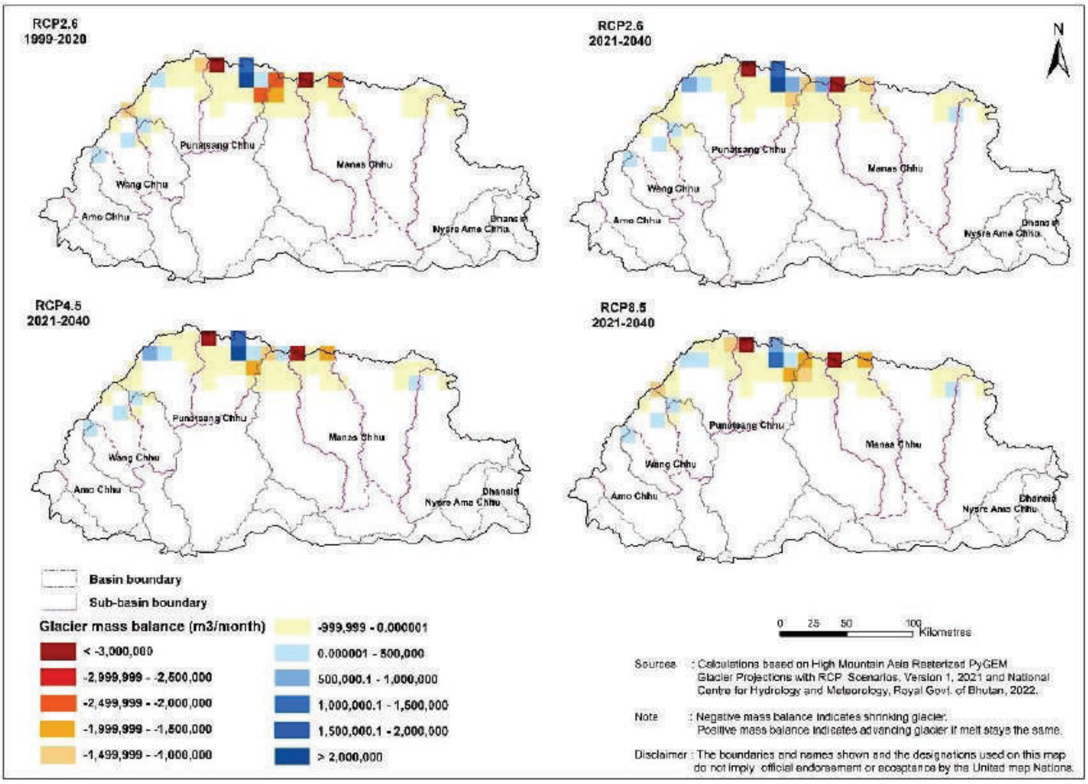


Figure 34 Spatial distribution of projected glacial total mass balance under RCP2.6, RCP4.5 and RCP 8.5 by 2040

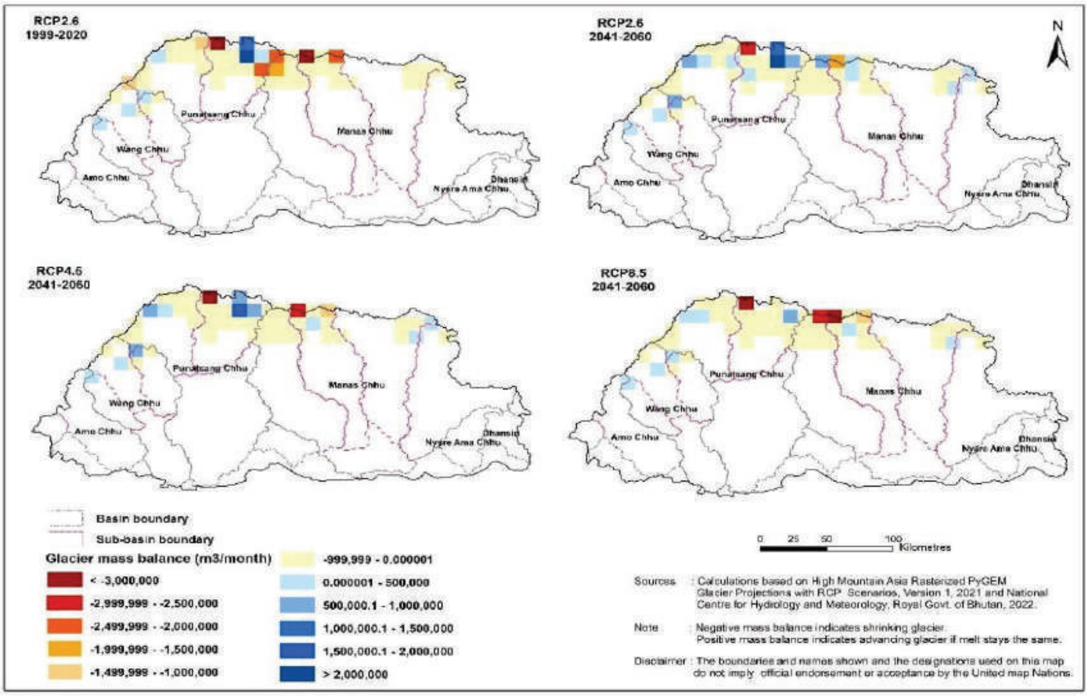


Figure 35 Spatial distribution of projected glacial total mass balance under RCP2.6, RCP4.5 and RCP 8.5 by 2060

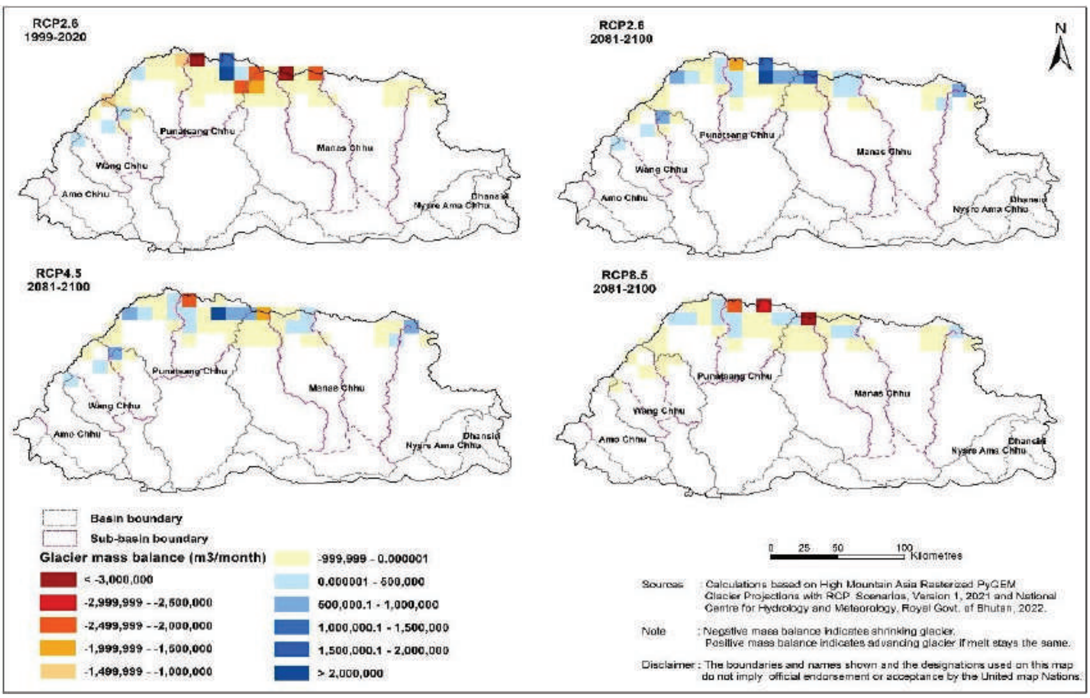
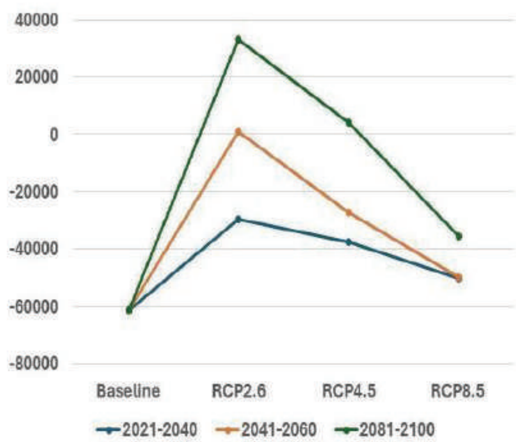


Figure 36 Spatial distribution of projected glacial total mass balance under RCP2.6, RCP4.5 and RCP 8.5 by 2100

4.3.2 Glacial runoff

The glacial runoff in Bhutan holds immense significance for both the region's environment and its people with respect to water supply, hydropower, and agriculture. However, climate change and associated rising temperature are changing the glacial runoff which can impact the population and infrastructure downstream. The glacial mass budget has a significant role in runoff generation in glacierized areas and numerous rivers rely on the glacial runoff for the supply of water[18]. Figure 37 represents the changes in glacial mass balance (left) and resulting changes in glacial runoff in Bhutan under different climate change scenario[19]. The glacial mass balance is likely to increase under the best-case scenario (RCP 2.6) which demonstrates the stringent pathways to reduce carbon emissions by 2020. However, under RCP 4.5 and 8.5 the mass balance is projected to decrease until the end of this century. As a consequence, decreased mass balance is likely to increase the runoff in the basins at the beginning, but decreasing mass balance of the glaciers is likely to accelerate the glacial retreat which might lead to reduced glacial runoff in the higher emission and long-term scenario.



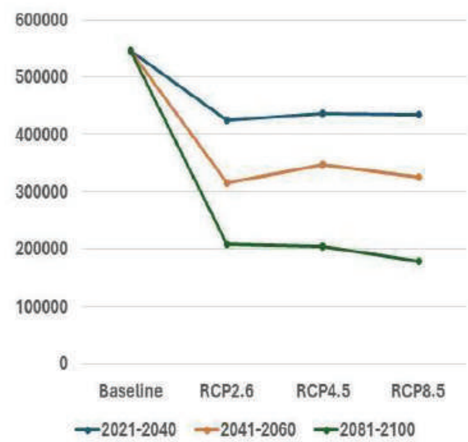


Figure 37 Projected glacier Total Mass Balance (m3/month) (left) and Projected glacier mean Runoff (m3/month) (right) under baseline, RCP 2.6, RCP 4.5 and RCP 8.5 climate change scenario

By 2040, as the mass balance is likely to decrease from RCP2.6 to RCP4.5, the runoff in the major basins in Bhutan increases. However, as the mass balance reduces more under RCP 8.5, the runoff decreases due to less availability of water in the glaciers.

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[18] Bhattacharya, A., Bolch, T., Mukherjee, K. et al. High Mountain Asian glacier response to climate revealed by multi-temporal satellite observations since the 1960s. Nat Commun 12, 4133 (2021). https://doi.org/10.1038/s41467-021-24180-y

[19] The transboundary effects are not considered in this analysis

Wang Chhu basin has the highest reduction in runoff (Avg. 30%) followed by Manas Chhu (Avg. 24%) and Punatsang Chhu (Avg. 17%). Among the sub-basins Drnagme Chuu of the Manas basin is likely to face highest decrease in glacial runoff (~78%) by 2040 (Figure 38).

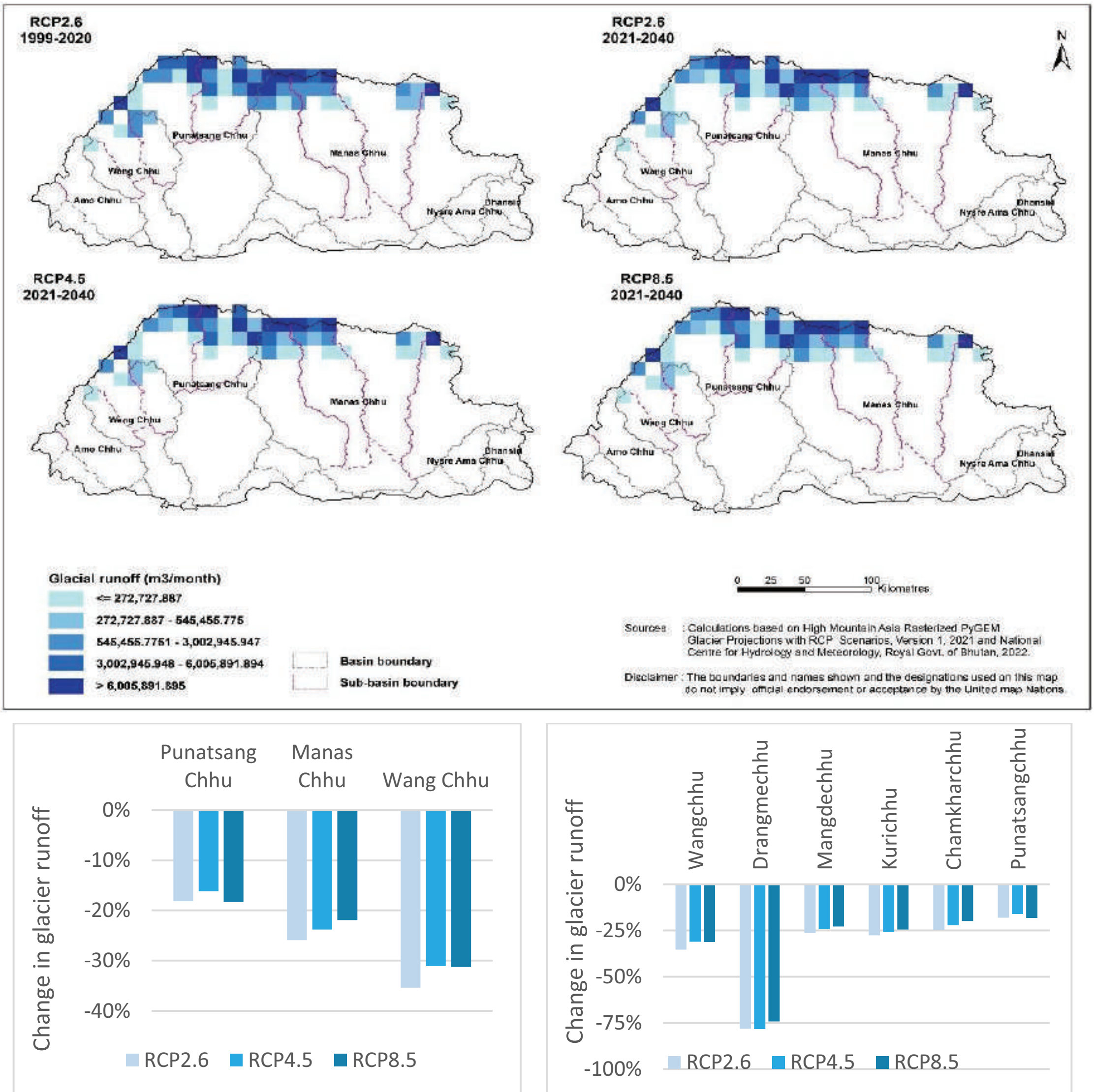


Figure 38 Spatial distribution of projected glacial runoff under RCP2.6, RCP4.5 and RCP 8.5(top) and resulting change in basin-wise (bottom left) and sub-basin-wise (bottom right) water availability by 2040 in Bhutan

The glacial runoff is likely to decrease further across all the river basins by 2060 with the highest decrease in the Wang Chhu basin (~52%) followed by Manas Chhu (~45%) and Punatsang Chhu (~35%). The comparative increase in the runoff from RCP2.6 to

RCP4.5 is due to a sharp decrease in mass balance. But under RCP8.5, the impact of retreating glaciers is visible through further decrease in runoff. Water availability from glacier run off is likely to decreases further in all sub-basins with the highest likely decease in Drangme Chhu (~91%) by 2060 (Figure 39).

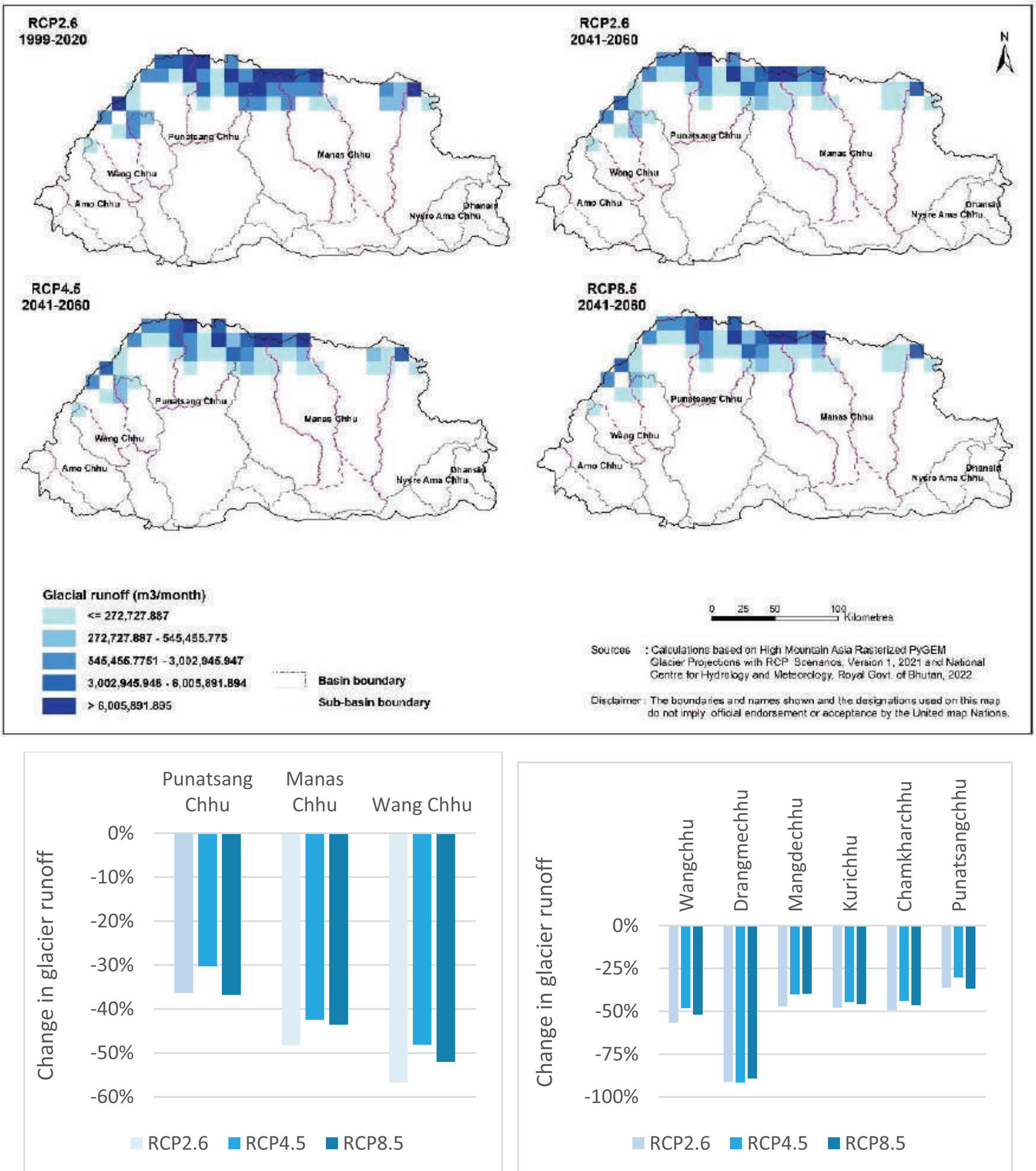


Figure 39 Spatial distribution of glacial runoff under RCP2.6, RCP4.5 and RCP 8.5 (Top) and resulting change in basin-wise (bottom left) and sub-basin-wise (bottom right) water availability by 2060 in Bhutan

In the long-term, the glacier runoff in all the river basins is likely to decrease further. Wang Chhu river basin is likely to receive around 67% less runoff from baseline. The Manas Chhu and Punatsang Chhu are likely to receive 68% and 59% less runoff respectively and Drangme Chhu sub-basin is likely to receive up to 98% less runoff compared to the baseline by 2100 (Figure 40).

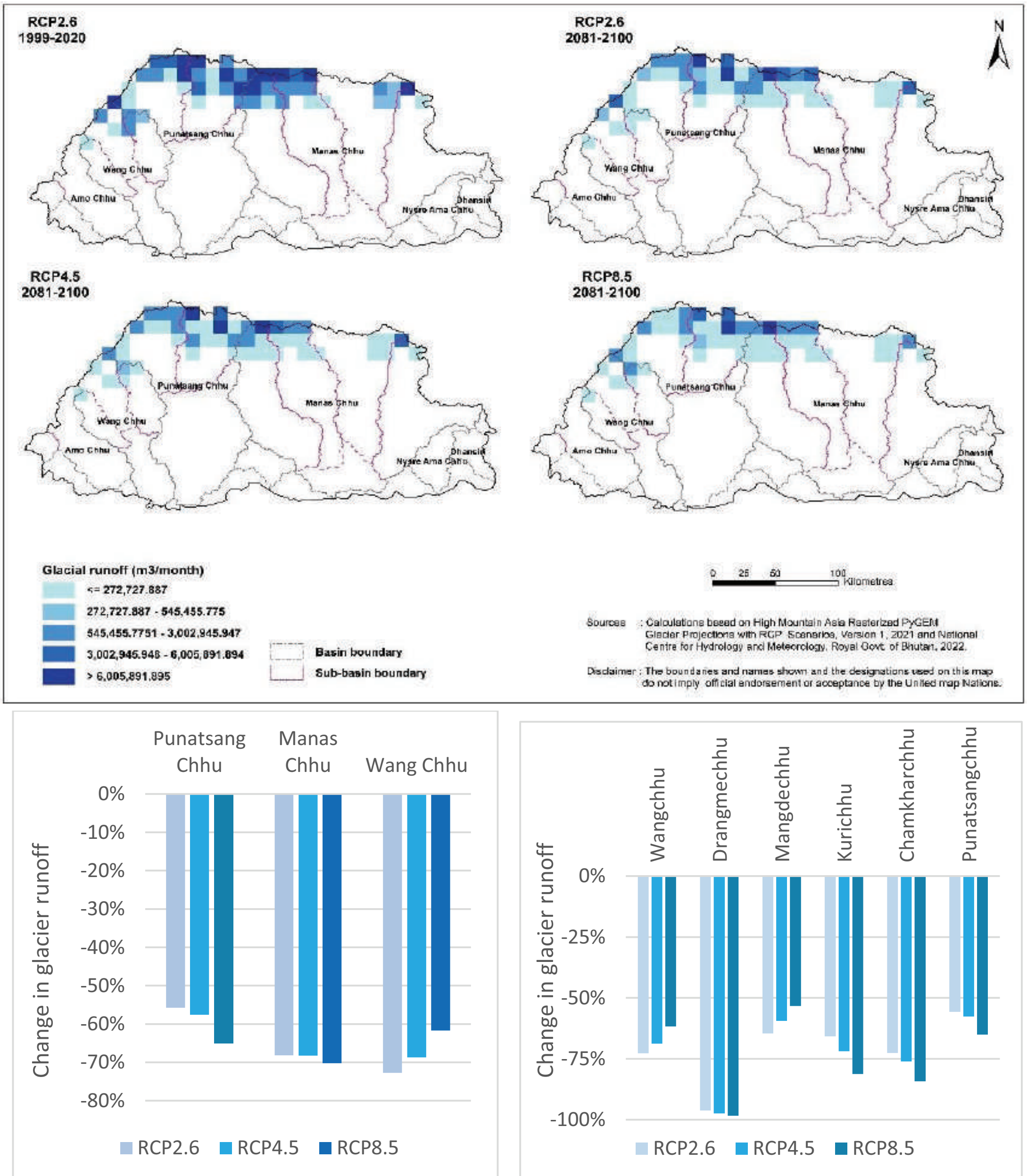


Figure 40 Spatial distribution of glacial runoff under RCP2.6, RCP4.5 and RCP 8.5(Top) and resulting change in basin-wise (bottom left) and sub-basin-wise (bottom right) water availability by 2100 in Bhutan

5 Regional and sectoral impacts

In Bhutan, the most climate sensitive sectors are agriculture, hydropower and forestry. Moreover, the initial impacts of extreme events are often directly felt by the population, particularly in the form of health risks and disruptions to daily life. With this background this section will demonstrate the following examples of regional and sectoral impacts which are assessed based on the climate projection analysis explained in the previous sections.

- Exposure of population to increased monsoon precipitation to understand the impacts of potential flood situations under future climate scenarios.
- Exposure of agriculture to increased monsoon precipitation to understand the impacts of potential flood under future climate scenarios.
- Exposure of rice production to increased monsoon precipitation to understand the impacts of potential flood under future climate scenarios.
- Exposure of population to increase summer Tmax to understand the impacts of potential heatwave like situation under future climate scenarios.
- Exposure of forests to increase summer Tmax to understand the impacts of potential forest fire situation under future climate scenarios.
- Exposure of hydropower to reduced glacial runoff under future climate scenarios.

5.1 Population

The Worldpop gridded population data (unconstrained UN adjusted) with 100m spatial resolution is used to assess population exposure. Figure 27 represents population exposure to high to very high increase in monsoon precipitation under SSP3 7.0, 2021-2040 and the trend of population exposure under different climate scenarios. The overall trend of population exposure shows an increasing pattern for all the scenarios across the timescale. However, the exposure reduced for SSP2 scenario for both near and mid-term as the area under high to very high increase in monsoon precipitation also decreases (Figure 12). Around 99% of the total population are exposed to a high to very high increase in precipitation by 2100 under all scenarios (Figure 41).

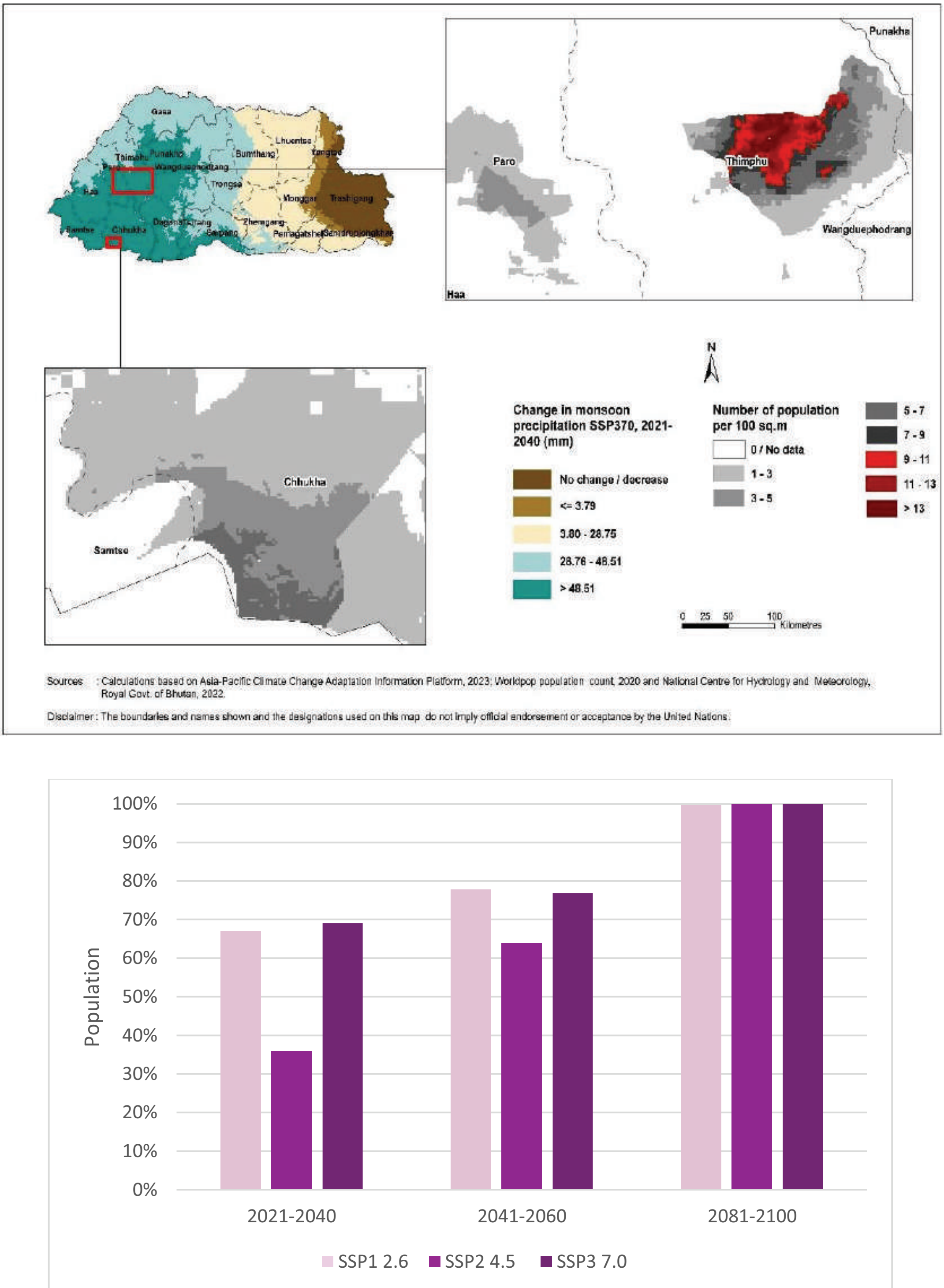


Figure 41 Population exposure to high to very high increase in monsoon precipitation under SSP3 7.0, 2021-2040 (top) and the trend under different climate change scenarios (bottom)

At the subnational level population exposure varies in different districts. The population exposure to the highest increase in monsoon precipitation for the top five mostly populated districts are shown in Figure 28. Among them Thimphu has the highest population (~16% of total population) and almost 100% of them are exposed to high increase in precipitation across all the scenarios except SSP1 and SSP2 in the near-term. Chhukha with ~12% and Samtse with ~8% of total population are exposed to high increase in precipitation across all the scenarios. The exposure increases in the mid-term and long-term scenario. Trashigang, on the other hand, with the fourth highest population (~7% of total population) is likely to face a decrease in monsoon precipitation across all the scenarios except SSP3 2081-2100 (Figure 42) (section 4. 1.2).

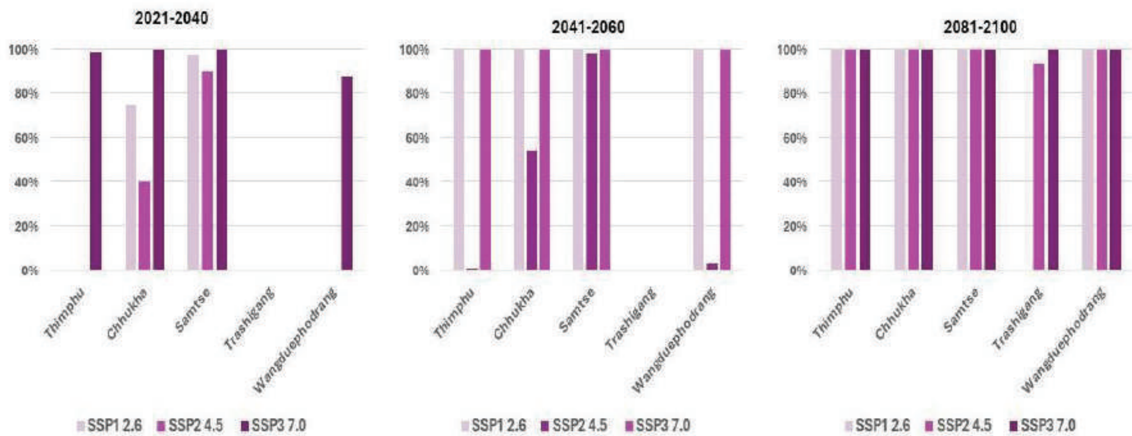


Figure 42 Exposure of top 5 populated districts to very high increase in monsoon precipitation by 2040, 2060 and 2100 under different climate change scenario

The population exposure to summer maximum temperature is assessed to understand the potential impacts of heatwave like situation in Bhutan. In general, Thimphu has the highest population (~16% of total population). More than 95% of the population of Thimphu are likely to be exposed to 1-1.5 °C increase in summer temperature by 2040, 1.5-2°C by 2060 and 3.5-4 °C by 2100 under SSP3 7.0. ~40% of the total population of Bhutan (in Bumthang, Gasa, Lhuentse, Paro, Punakha, Thimphu, Trongsa, Wangdue Phodrang and Trashi Yangtse) are likely to be exposed to more than 4 °C increase in maximum summer temperature by 2100 under SSP3 7.0.

As the southern part of the country has higher summer temperature, further increase in temperature may create a heatwave like situation. According to the climate projection the Tmax for summer is likely to reach 2°C in the southern districts namely Chhukha, Dagana, Pema Gatshel, Samdrup Jongkhar, Samtse, Sarpang, Tsirang and Zhemgang by mid-term under SSP2 4.5 scenario exposing almost entire population of these districts. In the SSP2 4.5, long-term around 74% population are likely to be exposed to 2 to 2.5 °C increase in summer Tmax and 25% to 2.5 to 3 °C higher Tmax. Under long-term SSP3 7.0, 78% of the population are likely to be exposed to a 3 to 3.5 °C increase in summer Tmax and 22% to 3.5 to 4 °C higher Tmax in summer (Figure 43).

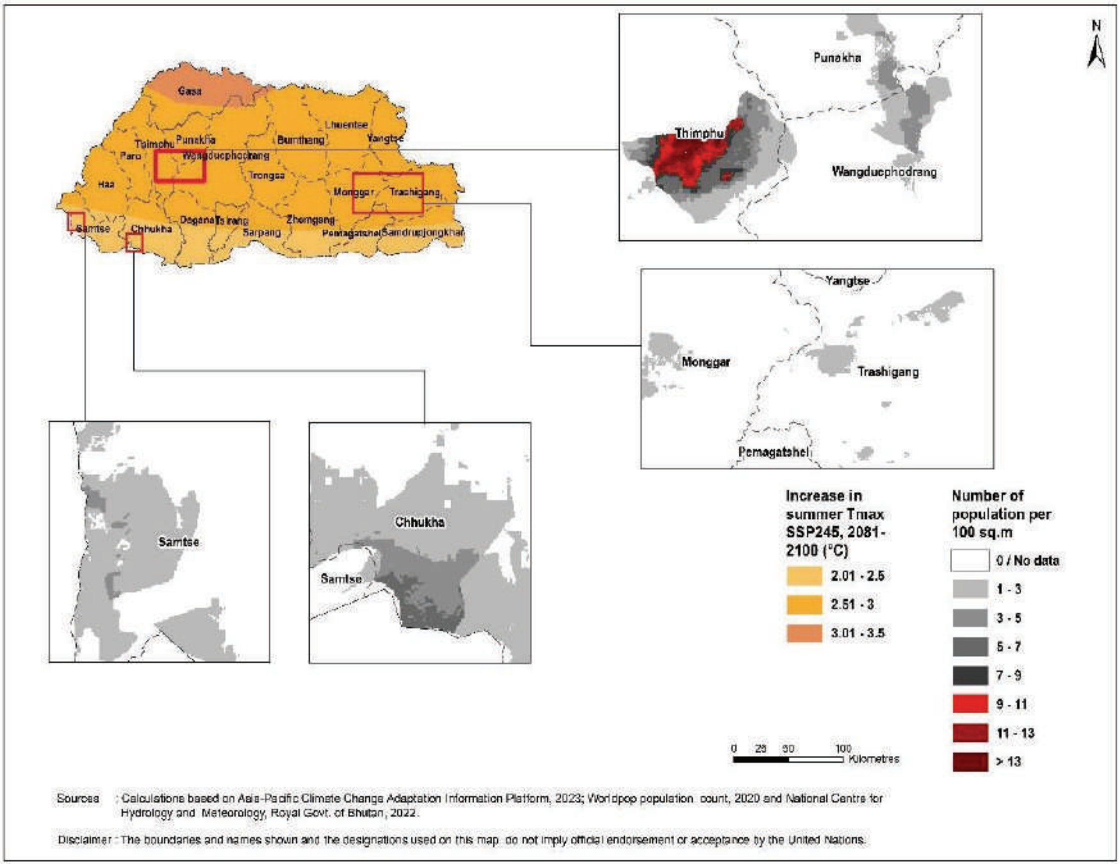


Figure 43 Population exposure to high to very high increase in summer Tmax under SSP2 4.5, 2081-2100

5.2 Agriculture

In Bhutan 49.2% of population is employed in the agricultural sector. 58% of the total population engaged in agriculture are female[20] and agriculture sector is the highest contributor to the nation's economy. Agriculture in Bhutan is scattered along the valleys mainly concentrated in the central and southern part of the country. The eastern part is predominantly focused on dryland agriculture (Figure 38). The main cereal crops include rice, maize, wheat, barley, and millet. Apart from that seasonal fruits and vegetables are also grown in Bhutan. The agriculture is already facing multitude of inherent challenges in the mountainous ecosystem due to low soil fertility coupled with cold stress and frequent weather swings[21].

The impacts of climate change are likely to add additional burdens on the agriculture sector in Bhutan. Although monsoon season is one of the major sources of water for agriculture, increased precipitation leading to flood and flash flood can damage crops, cause outbreaks of diseases and pests, damage irrigation channels and affect local food security. Around 54% and 66% of the total agricultural areas are exposed to a high increase in monsoon precipitation by 2040 and 2060 respectively under the SSP3 scenario.

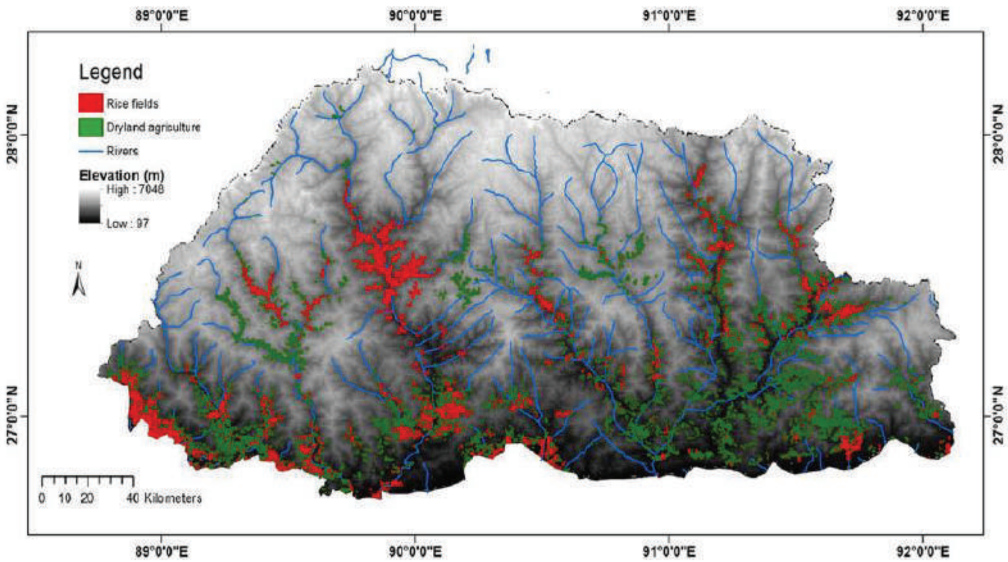
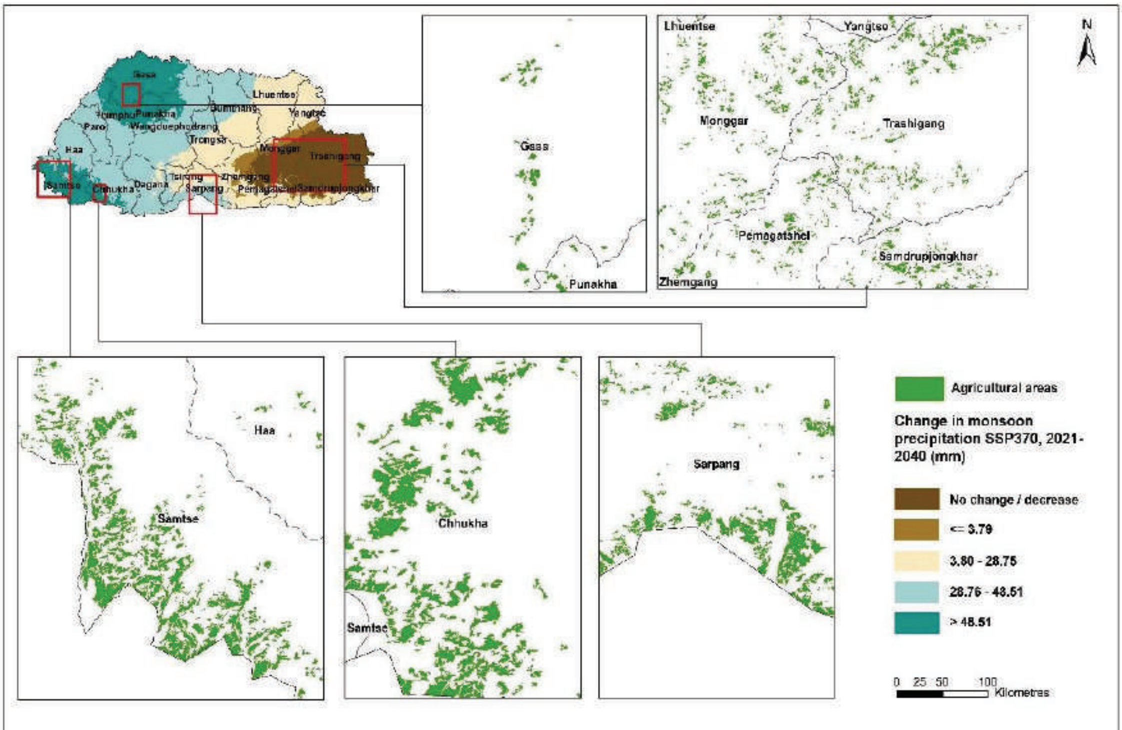


Figure 44 Map of Bhutan highlighting scattered agricultural land parcels in slopes and river valleys [15]

[20] https://www.nsb.gov.bt/wp-content/uploads/dlm_uploads/2022/04/LFS-2021-web.pdf

[21] https://agricultureandfoodsecurity.biomedcentral.com/articles/10.1186/s40066-018-0229-6

Figure 45 identifies the areas with significant agriculture exposed to high to very high increase in monsoon precipitation under SSP3 7.0, 2041-2060. Some of the districts in the west and south-western part of the country with large areas under agriculture are likely to be exposed to high to very high increase in precipitation whereas the south-eastern part might face a deficit in monsoon rainfall which also has large areas under agriculture. The chart shows that there is an increasing trend in the exposure of agricultural areas to increase in monsoon precipitation across the scenario under each timescale. Around 54% and 66% of the total agricultural areas are exposed to a high increase in monsoon precipitation by 2040 and 2060 respectively under the SSP3 scenario.



Sources : Calculations based on Asia-Pacific Climate Change Adaptation Information Platform, 2023; Worldpop population count, 2020; National Centre for Hydrology and Meteorology, Royal Govt. of Bhutan, 2022 and National Land Comission Secretariats, 2020.

Disclaimer : The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations.

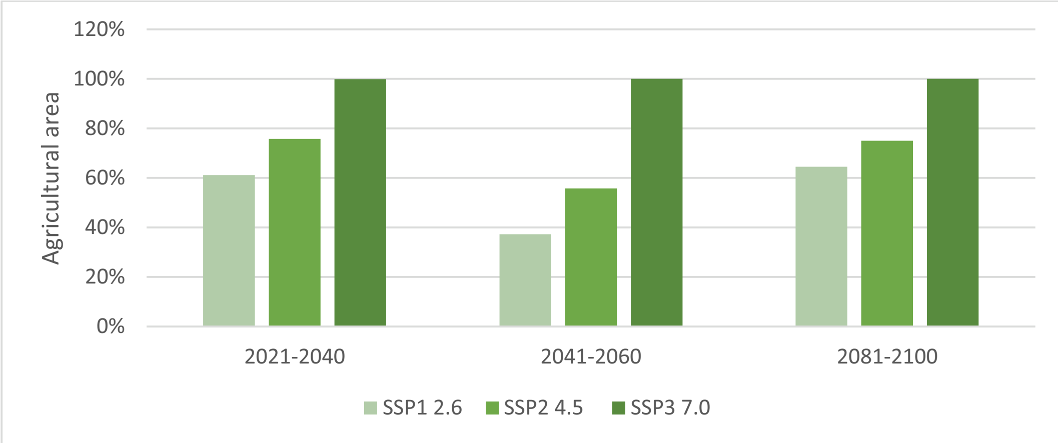


Figure 45 Exposure of agricultural areas to high to very high change in monsoon precipitation under SSP3, 2041-2060 (top) and the trend under different climate change scenarios (bottom)

Among the districts of Bhutan Samtse, Chhukha, Saprang, Dagana and Wangdue Phodrang tops the list with respect to area under agriculture. Samtse has the highest area under agriculture (~13%) which is exposed to very high increase in precipitation across all the scenarios. Chhukha and Sarpang with ~8% of total agricultural area are exposed to high to very high increase in precipitation across all the scenarios. By 2100, all the agricultural areas in all top 5 districts are exposed to high to very high increase in monsoon precipitation. On the other hand, Trashigang with one of the highest agricultural areas (~6%) is likely to face a decrease in monsoon precipitation by up to 30mm and 22mm under SSP2 (2060) and SSP3 (2040). By 2100, all the agricultural lands are exposed to a very high increase in monsoon precipitation (Figure 46).

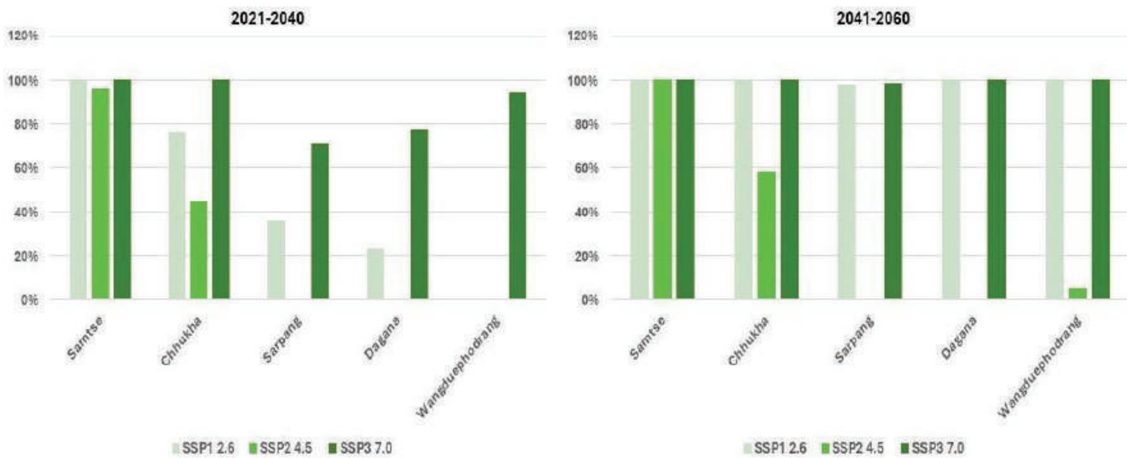
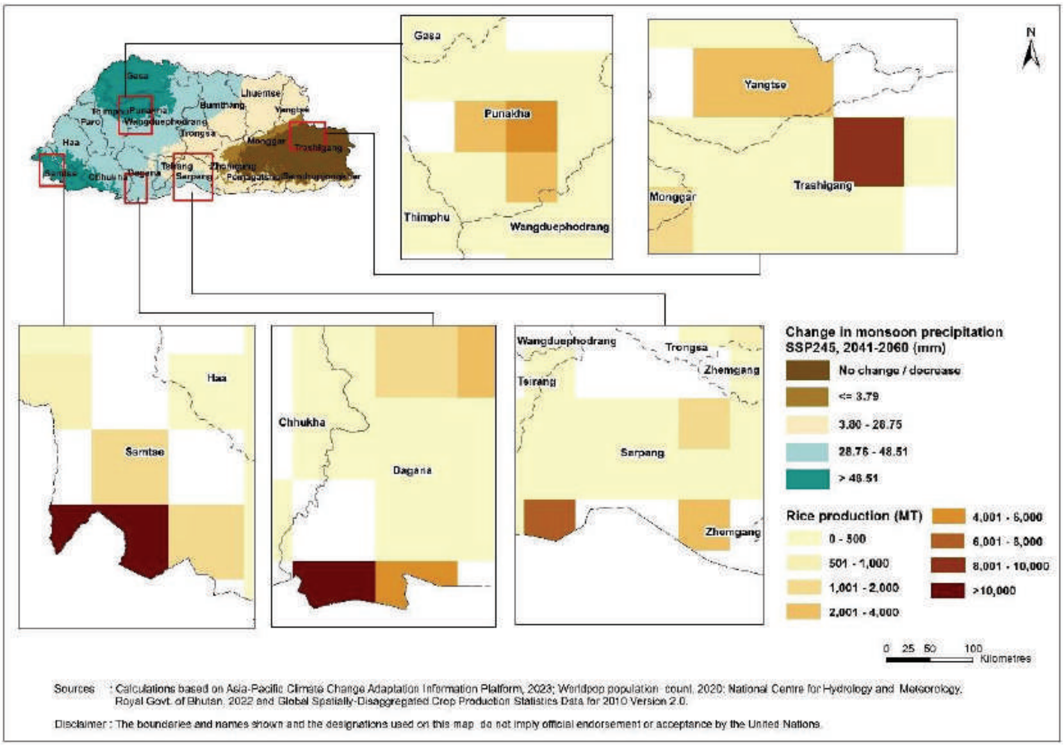


Figure 46 Exposure of top 5 districts with agricultural areas to very high increase in monsoon precipitation by 2040, 2060 and 2100 under different climate change scenario

Rice is one of the major crops in Bhutan which mainly depends on the monsoon precipitation. Increase in monsoon precipitation might create flood like situation affecting the rice production. Exposure of rice production to high to very high increase in monsoon precipitation increases from 2021 to 2100 across all the scenarios. By 2040 up to 75% and by 2100 around 100% of the total rice production are likely to be exposed to a high increase in monsoon precipitation under SSP3 scenario (Figure 47).



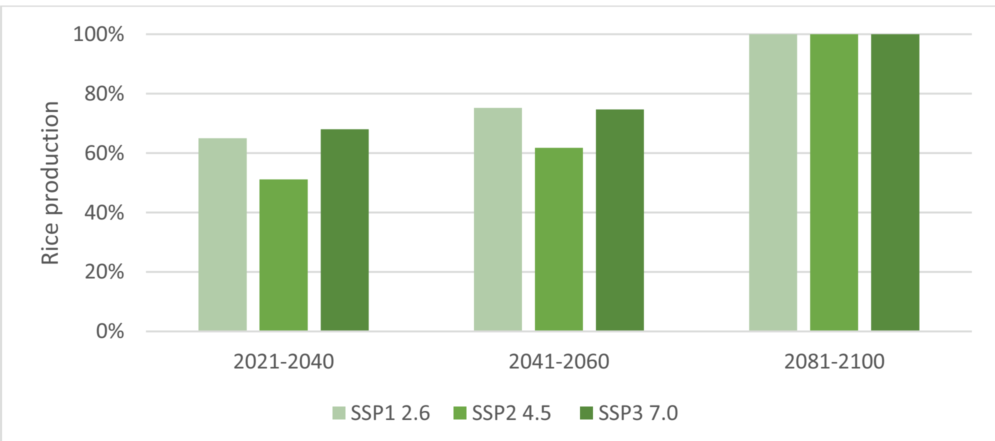
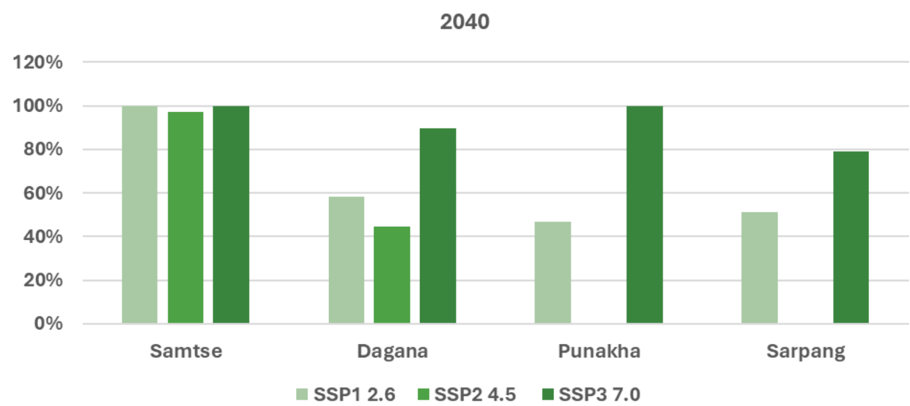


Figure 47 Exposure of rice production to high to very high change in monsoon precipitation under SSP2 4.5, 2041-2060 (top) and the trend under different climate change scenarios (bottom)

Rice is mainly produced in the summer monsoon season in Bhutan. Samtse tops the list in rice production (~17% of total rice production) The entire rice production in Samtse is exposed to very high increase in precipitation across all the scenarios. Dagana, Punakha and Sarpang with ~13%, ~11% and ~10% of total rice production of the country respectively are exposed to high to very high increase in monsoon precipitation across all the scenarios. By 2100, in all the top four rice producing districts namely Samtse, Dagana, Sarpang, Punakha, the entire rice production is likely to be exposed to high to very high increase in monsoon precipitation. On the other hand, Trashigang, one of the highest rices producing districts (~8% of total production) is likely to face a decrease in monsoon precipitation by 2060, but will experience increase in monsoon precipitation of ~50mm by 2100 (Figure 48).



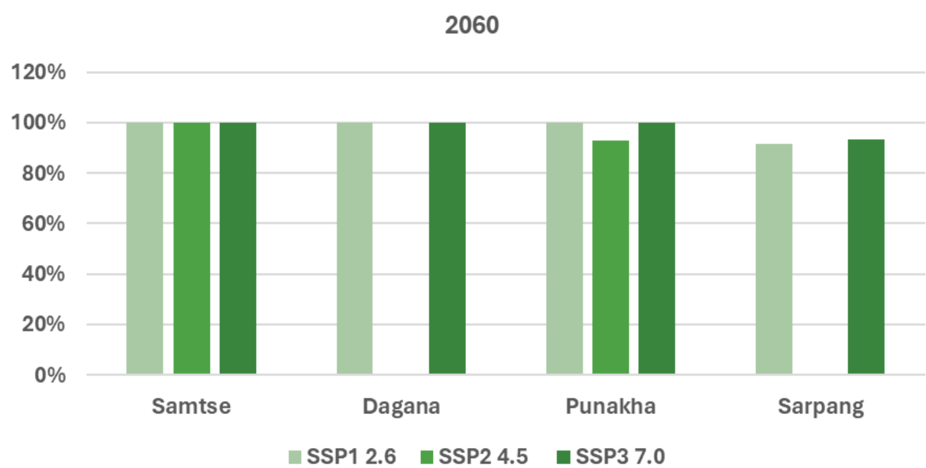


Figure 48 Exposure of top 5 rice producing districts to very high increase in monsoon precipitation by 2040 and 2060 under different climate change scenario

6 Recommendation for adaptation and mitigation strategies

Climate change adaptation can propel three dividends bringing about economic, social and environmental benefits[22]. Adaptation measures not only help avoid losses caused by disasters, proving to be economically beneficial in the short-term, but enhanced resilience and future risk reduction are long-term benefits which are reflected in the social and environmental sectors. Based on the Global Commission on Adaptation Report (2019). Five priority areas of adaptation can be proposed which are improving dryland agriculture crop production strengthening, enhancing water and energy security, early warning systems, enhancing water and energy security, developing climate-resilient infrastructure and adopting nature-based solutions. Agriculture (including forestry and livestock) and hydropower are two highly climate sensitive sectors which also contribute the most in Bhutan's economy[23]. With this purview two different approaches of implementing the adaptation measures in Bhutan are depicted in Figure 52.

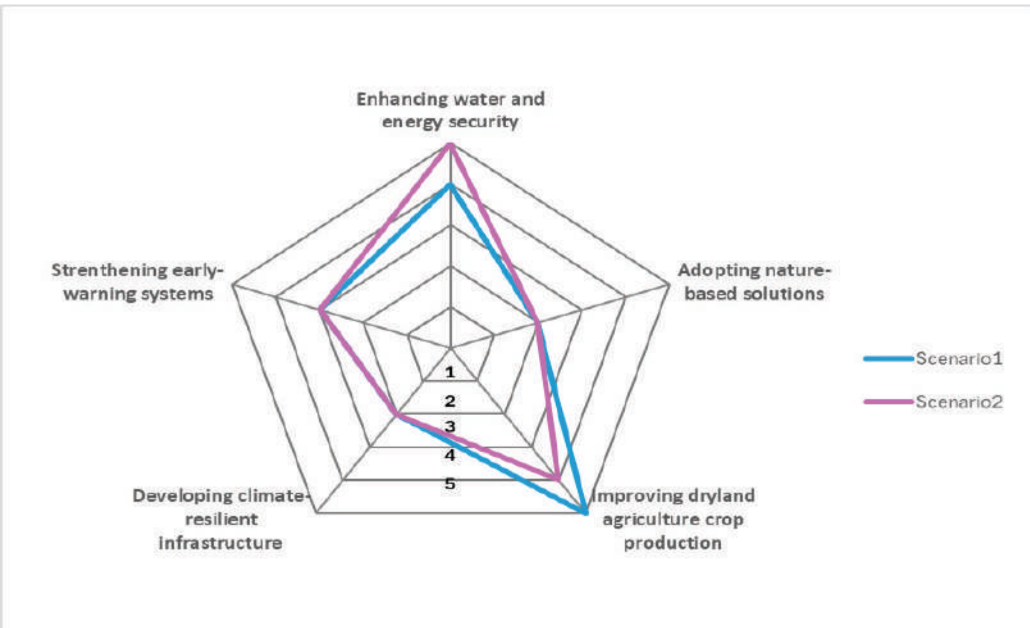


Figure 49 Five priority areas for climate change adaptation in Bhutan

22 https://gca.org/about-us/the-global-commission-on-adaptation/

23 Budget Report for FY 2022-23, Bhutan https://www.mof.gov.bt/wp-content/uploads/2022/06/Budget-Report-for-FY-2022-23-in-English.pdf

6.1 Scenario one: People centric approach

This approach describes a people centric approach wherein top adaptation priority is on improving dryland agriculture crop production followed by enhancing water and energy security, strengthening early warning systems, developing climate-resilient infrastructure and adopting nature-based solutions. The topmost priority is on the agriculture sectors as nearly 50% of the country's population is employed in the agricultural sector[24,25]. Drylands agriculture is practiced mainly in the south-eastern districts of Bhutan along with water intensive crops like paddy in monsoon and irrigated crops like wheat and mustard in dry season (Figure 30)[26].

The sources of irrigation are mainly rain-fed. Trashigang district is one of the highest rice producing areas in the country. According to the climate projection analysis, precipitation in the main monsoon months of June and July rainfall in this region is likely to decrease than normal impacting both the in-season agriculture as well as the sources of irrigation. Moreover, the availability of water from glacial runoff is also likely to decrease more in this part of the country. Drylands are susceptible to degradation, with a decline in the soil's water-holding capacity and fertility, reducing agricultural output and increasing the land's vulnerability to drought or water scarcity situations. This can be addressed by integrated spatial land-use planning and a multidisciplinary approach to land management. This can include practices like integrated soil fertility management and watershed management to reduce soil erosion and run off, rainwater harvesting, vegetation management and sustainable forest management. Impact-based forecasting based on seasonal forecast can provide the farmer's risk information for early action. In the mid and long-term as more monsoon rain is likely in August and September early action such as adjustment of crop calendar can avoid potential losses and crop damage. On the other hand, monsoon rainfall is likely to increase more long-term and high emission scenarios in the near and mid-term making wet areas become wetter especially in June and July. The southern part needs flood management strategies focused on the already flood prone districts to protect the monsoon crops from damage.

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[24] https://kuenselonline.com/employment-in-agriculture-continues-to-decline/

[25] https://www.nsb.gov.bt/wp-content/uploads/dlm_uploads/2022/04/LFS-2021-web.pdf

[26] CC risk assessment on agriculture pdf

6.2 Scenario two: Economic resilience approach

The scenario 2 describes an economic resilience approach which prioritizes water and energy security the highest. Hydropower is a strategic national resource in Bhutan because of its contribution to the country's economy (14.3%) along with the water sector as well as immense social and economic benefit to the remotest corners of the country. Around 70% of Bhutan's hydropower generation is exported mainly to India. Currently99, 5% electricity is generated through hydropower from six major hydropower projects. Major expansion of the hydropower sector is planned. The hydropower sector is highly dependent on the monsoon rainfall and runoff from the glaciers. Global warming and related increasing temperature are accelerating the glacier melt which initially may supply more water in the streams, but in long-term the glacial retreat may cause reduction in water availability not only in the rivers but also in the entire ecosystem (section 3.4). Moreover, they are also vulnerable to climate extremes, such as floods, intense monsoons, and glacier dam bursts in summer, followed by drought in winters.

The Royal Government of Bhutan has already adopted the Bhutan Sustainable Hydropower Development Policy (2021) to enhance the energy security in the country with the aim of boosting the country's economy along with developing sustainable energy sources to help with climate change mitigation. However, the planning of the hydropower project should be well informed with the risk related to climate change and their impacts. With the probabilities of reduced water availability in the future, strategic interventions and innovative mechanisms are necessary to sustain energy production during adverse climate conditions. Smart and integrated management of watersheds and catchment area protection are necessary to make hydropower development a climate resilient undertaking in times to come. Moreover, all the hydropower infrastructure investment must be risk-informed. In this regard, as recommended by ESCAP a three-pillar approach: dynamic scenario planning, lifecycle assessments and multi-stakeholder engagement, with multiple interdependencies among the three pillars could be adopted[27].

[27] ESCAP (2022). Pathways to Adaptation and Resilience in South and South-West Asia.

In the first National Adaptation Plan (NAP) prepared in Bhutan seven cross-cutting sectors were identified which are water, agriculture and livestock, forest and biodiversity, human settlement and climate smart cities, health, energy and, climate services and disaster risk reduction. Out of the total estimated financial needs for the proposed adaptation plan in the first NAP the highest proportion was allotted for was assessed for human settlement and climate smart cities (~94%) which highlights the need for the climate resilient infrastructures. Among the rest of the sectors water and energy have been given second highest priority in terms of investments followed by agriculture and livestock, forest and biodiversity and lastly the climate services and DRR (Figure 53). However, looking at the current risk profile, the financial priorities need to be modified with enhanced investment in the agriculture, water and energy sector to build resilient society as well as national economy. The investment in climate services and DRR also needs to be enhanced to leave no one behind at risk, especially in challenging topography and remote areas of the country.

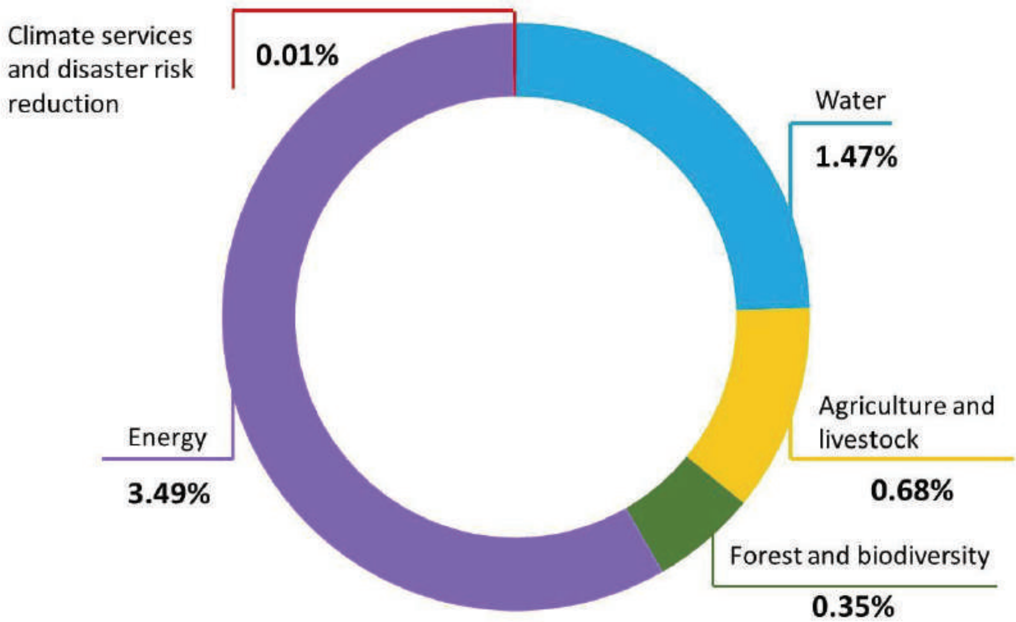


Figure 50 Sectoral focus of adaptation actions and assessed financing need as per first NAP in Bhutan

7 Analysis of Policy and regulatory framework

Policy analysis is a valuable tool for organizations to assess and improve their existing policies. It helps to identify gaps in the policies, highlights areas where there is a lack of clear guidelines or where policies need to be developed as well as ensures that policies are comprehensive, relevant, and aligned with the goals. Following section reviews three main policies relevant to climate change and climate actions in Bhutan.

7.1 Bhutan's National Adaptation Plan

Bhutan's first National Adaptation Plan (NAP) was officially launched on September 16, 2023. This significant move places Bhutan alongside 16 other Least Developed Countries that have successfully launched their key climate adaptation plans. The NAP aims to integrate medium and long-term climate adaptation priorities into Bhutan's development planning, enhancing the country's resilience to climate change impacts. This plan is pivotal in guiding Bhutan towards embedding adaptation in core development decision-making processes, ensuring resilience against climate shocks for people, places, ecosystems, and economies.

The NAP process, initiated in 2019 with the support of a US$ 2.7 million project funded by the Green Climate Fund and UNDP, addresses climate risks across seven vulnerable sectors: water, agriculture and livestock, forests and biodiversity, human settlement and climate-smart cities, health, energy, climate service, and disaster risk reduction. Through comprehensive risk assessments, the plan identifies strategic adaptation priorities, marking a shift from project-based interventions to more systematic, programmatic approaches for long-term resilience. It proposes integrating these priorities into national, sectoral, and local development plans, making this initiative a cornerstone for future environmental and developmental policy-making.

The launch was described as timely and is expected to play a crucial role in planning and prioritizing adaptation strategies for Bhutan's 13th Five-Year Plan, aligning with the goals of the Paris Agreement. The implementation of the NAP, however, is a daunting task that requires significant technical and financial support. An estimated $14 billion is needed to finance the climate adaptation measures outlined in the NAP over the next 15 years. Despite these challenges, the NAP represents Bhutan's commitment to maintaining its ecological balance and carbon-neutral status while pursuing sustainable development guided by the principles of Gross National Happiness.

7.2 Nationally Determined Contribution (NDC)

Bhutan's second Nationally Determined Contribution (NDC), submitted in June 2021, reaffirms the country's commitment to remaining carbon neutral, a goal it has upheld since 2009. This updated NDC enhances Bhutan's mitigation targets and actions through the introduction of Low Emission Development Strategies (LEDS) in several key sectors: human settlement, food security, industries, and surface transport. These strategies focus on decoupling economic growth from greenhouse gas emissions via clean technology, innovation, renewable energy, and green jobs creation.

The Climate Action Tracker notes that Bhutan's second NDC presents a stronger target compared to its first, providing greater detail on mitigation measures that the country seeks to implement with international support. Bhutan aims not only to maintain its carbon neutrality but also to remain net negative in carbon emissions. This involves detailed planning and international cooperation to manage and reduce emissions in various sectors, including agriculture, human settlements, and transportation, aiming for a cumulative emissions reduction potential of approximately 20 MtCO2e between 2021-2030.

Key highlights from Bhutan's NDC include the reaffirmation of its carbon neutral status, improved data demonstrating its net carbon sequestering capabilities, and the setting of additional targets on the National REDD+ Strategy (NRS) for managing forest carbon stock. The NDC also outlines low emission development strategies in priority sectors such as food security, human settlements, industries, and surface transport. It emphasizes the importance of international support for maintaining Bhutan's carbon neutral status and highlights the conditional nature of the measures in the NDC on such support.

Bhutan's commitment to environmental sustainability and carbon neutrality serves as an example of proactive climate action. The country's efforts underscore the importance of international cooperation and support in achieving ambitious climate goals, especially for nations with limited resources but a strong commitment to sustainable development.

To mitigate the detrimental impacts of climate, Bhutan addresses climate change mitigation actions in the form of LEDS, roadmaps and strategies as presented below.

A) Forest conservation and management under the National REDD+ Strategy

Bhutan has developed a comprehensive REDD+ strategy, including a National REDD+ Strategy and supporting mechanisms, aimed at achieving REDD+ goals while providing additional benefits such as livelihood enhancement, ecosystem service protection, and biodiversity conservation. The NRS emphasizes preserving forests and enhancing climate change adaptability without hindering economic growth. To fulfill this vision, Bhutan proposes four strategic approaches namely strengthening Forest Management Practices, Climate Smart Primary Production, Integrated Land Use Planning and Improved Rural Livelihoods. Despite limited deforestation, Bhutan focuses on forest management and landcover protection as strategic, cost-effective measures, offering valuable insights for sustainable natural resource management globally.

B) Low Emission Development Strategy for Food Security

Historically, emissions from agriculture and livestock in Bhutan have been stable, contributing to 14.5% of the nation's total emissions. The sector's LEDS identifies six actions to lower emissions and enhance carbon sequestration, aligning with broader strategies outlined in Bhutan's NDC. These actions also aim to integrate mitigation efforts within sectoral activities, offering significant opportunities for socio-economic growth and poverty alleviation. The targeted measures up to 2030 have the potential to mitigate up to 710 Gg CO_2e cumulatively.

C) Sustainable Hydropower Development

Clean hydropower enables low GHG emissions from Bhutan and the achievement of carbon neutral status. Further development of hydropower projects can mitigate emissions beyond Bhutan in the region at large. Future development of hydropower will be as per the revised Sustainable Hydropower Policy 2021 and enhances climate resilience through reservoir/pumped storage schemes to ensure energy and water security.

D) Alternative Renewable Energy

An alternative renewable energy program consisting of mini hydro, solar, wind and waste-to-energy technologies will be pursued as a priority program with the aim to reduce deforestation in rural communities and diversify the energy portfolio as adaptation measure to changing water flows, particularly in the dry seasons through solar, wind, waste to energy and green hydrogen.

The National Energy Efficiency & Conservation Policy and the Energy Efficiency Roadmap (NEECP) were adopted in 2019. The roadmap establishes the impact of energy efficiency (EE) on the country's GHG emission in line with the first NDC targets with about 0.59 million tCO_2e emission reduction potential from implementation of EE&C measures. The action plan aims to contribute towards the NDC mitigation measures by enhancing demand side management through (i) promotion of EE in appliances, (ii) buildings and (iii) industrial processes and technologies. Several of the actions and measures in the EE policy and action plan are also being integrated into the different LEDS for human settlements, transport, and Industries.

7.3 Climate Change Policy of Bhutan 2020

The Climate Change Policy of Bhutan 2020 reaffirms Bhutan's commitment to remaining carbon neutral. It provides strategic guidance for adapting to climate change effectively and ensuring all stakeholders are meaningfully involved. The policy sets four main objectives: 1) maintaining carbon neutrality, 2) building resilience to climate change, 3) securing implementation means (finance, technology, capacity building, awareness), and 4) ensuring coordinated actions. It emphasizes the importance of integrating climate change measures into development plans and policies, with a special focus on vulnerable groups and sectors.

For agriculture, the policy aims to manage greenhouse gas emissions in a way that doesn't compromise food production, contributing to food and nutritional security. It emphasizes the importance of monitoring GHG emissions from the agricultural sector annually and assessing the carbon sink in forests and soils periodically.

Bhutan's Ministry of Agriculture and Livestock (MoAL) and Ministry of Energy and Natural Resources (MoENR) are two main ministries mandated with implementation of the climate change policy related to agriculture. MoAL has the mandate to enhance rural livelihoods and MoENR is the custodian of the forest resources of the country. They derive their mandate through several Acts, Policies and government directives (Seed Act, Biodiversity Act, Food and Nutritional Policy, National Forest Policy etc.). Their main actions are: management of forest and soils as carbon sinks and also as areas ecosystem-based adaption, management of emissions from agriculture and livestock sector, resilience of food, livestock sector and biodiversity.

Ministry of Industry, Commerce and Employment (MOICE) sets the agenda for the economic development of the country through the development of the manufacturing, trading, mining and energy sectors. MOICE aims for integration of low emission development strategies in energy and industry and provision of incentives for environmental performance.

8 Strategies for public awareness

Developing a climate change awareness strategy involves a multifaceted approach that addresses education, engagement, and action across different sectors and society. Although climate change affects everyone, those sectors or societies facing risk are more concerned. So, prior to deciding on the awareness strategies, assessment must be done to identify and prioritize the target groups. The strategies need to be customized based on the target groups and their priorities. The following are some of the key strategies for building community awareness on climate change.

8.1 Education and information dissemination

Bhutan's National Adaptation Plan (NAP) process, guided by the 2020 Skills Assessment for the NAP Process in Bhutan (SANP), has already identified integrating climate action into education as one of the key areas for improvement for climate action. In such a case, incorporating climate science and sustainability topics into school curriculums at all levels will ensure that students receive a thorough grounding in the causes, impacts, and solutions to climate change. The Ministry of Education and Skills Development (MoESD) is in the process of integrating climate change in the school curriculum from class IV to class XII.

Public Campaigns can be conducted using media, including social media, television, radio, and print, to disseminate factual and contextual information about climate change and potential risks relatable to the target groups, focusing on its local impacts and what individuals can do to help. Engaging voluntary youth organizations can play a pivotal role in information dissemination as well as in awareness programs on climate change. Workshops and seminars can be organized involving experts educating the public and specific groups (e.g., farmers, business owners) about climate change's impacts on their sectors and how they can adapt or mitigate those effects. Influencers, celebrities, and community leaders can be involved to spread awareness and model sustainable behaviors.

Lack of motivation is one of the main barriers to public participation in climate change[28]. In such a case linking the issues directly to their day-to-day concerns, particularly the impacts on their earnings can help motivate people to take actions by themselves. Solution oriented messages would be more effective rather than alarming the bell without providing solutions. Information dissemination in simple messages preferably in the local language will be better accepted and relatable rather than heavy jargon and unnecessary details.

8.2 Community engagement and empowerment

In addition to the government policies and plans, the community needs to be made aware of the risks, options that are available for a response, and be empowered to take their own actions. Effective public engagement is therefore key to success in planning for climate change.

Encouraging and supporting local initiatives aimed at sustainability, such as tree planting, renewable energy installations, or rainwater harvesting can enhance the effectiveness of the policies as well as motivate others to follow similar actions. Engaging the public in data collection related to climate change or community mapping can be effective to raise awareness on the impacts of climate change. Encouraging the use of traditional knowledge as part of building climate resilience and disaster risk management can empower the communities and ensure ownership of the climate actions.

Non-governmental organizations working with the communities can play an important role in building climate awareness among the locals by leveraging their expertise and networks for broader impact. Private sectors can promote sustainable practices, including reducing emissions, investing in green technologies, and adopting circular economy principles as part of their corporate social responsibility.

[28] https://link.springer.com/article/10.1007/s43621-021-00024-z

8.3 Innovation and technology

Promoting the adoption of solution-oriented pathways such as innovative technologies in renewable energy, energy efficiency solutions, and sustainable agriculture practices through incentives, subsidies, and support programs can encourage the public to be climate ready. Digital Platforms such as mobile applications and other online platforms to provide relevant resources can offer practical advice for reducing individual and collective environmental impacts. Audio-visual products for broadcast, print and online/social media can be used for information dissemination.

Annexure I

Risk, exposure and vulnerability

"**Risk** is the potential for adverse consequences for human or ecological systems, recognizing the diversity of values and objectives associated with such systems[29]." The risk related to climate change can arise either from the impacts of climate change or from the human responses to climate change and the consequences are manifested through the social, economic and cultural assets. In climate change, rise arises from dynamic interaction between climate related hazard with the exposure and vulnerability of the affected human or ecological system to the hazards. Hazards varies in magnitude and likelihood of occurrence and the exposure and vulnerability varies due to socio-economic changes and human decision-making, all of which governs the risk.

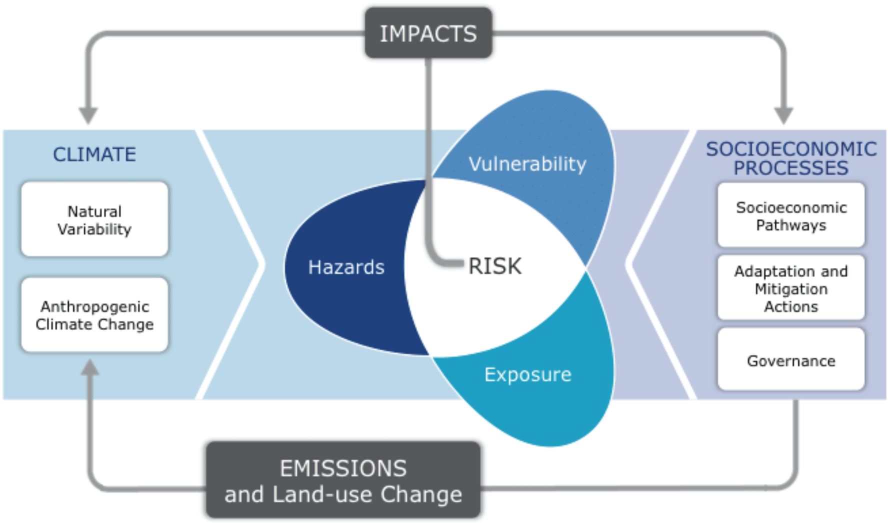


Figure 51 Risk as a function of hazard, exposure and vulnerability[30]

Risk is a function of hazard, exposure and vulnerability which is reflected through the impacts on the sectors (Figure 54). "Climatic **hazards** are agents of disaster in terms of what they may do to human settlements or to the environment". They include tropical cyclones, flood, thunderstorms, drought, rain, hail, snow, lightning, fog, wind, temperature extremes and sea level rise[31]. Hazards are often associated with economic, political, and social repercussions.

[29] Reisinger et al., "The Concept of Risk in the IPCC Sixth Assessment Report: A Summary of Cross-Working Group Discussions."
[30] IPCC, "Climate Change 2014: Synthesis Report."
[31] Hobbs, "Climatic Hazards."

Exposure refers to the assets, resources and infrastructure that are adversely affected by the hazards. According to Intergovernmental Panel on Climate Change (IPCC) for exposure states that it is "the nature and degree to which a system is exposed to significant climate variations[32]." Exposure to a hazard refers to the number of assets, resources and infrastructure in areas affected by hazard. e.g., the number of populations living in the flood affected area or in the areas projected to be affected by flood due to climate change and its impacts will define the population exposure to flood.

Vulnerability to climate change is "the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes". Societies or systems with less coping capacity are more vulnerable to the impacts of climate change. Some of the key vulnerabilities are associated with many climate-sensitive systems like employment, food supply, infrastructure, health, water resources etc.

Shared Socio-economic Pathways

Socio-economic characteristics that influence greenhouse gas emissions in a standardized manner, give an indication of the societal pathways associated with different levels of warming. The SSP scenarios consist of five narratives that describe alternative pathways of global development. These narratives are based on qualitative and quantitative information, such as population, urbanization, GDP, education, health, and inequality. In this study three of them are chosen to have an overview of the best possible case to the worst- case scenario.

- **SSP1: Sustainability (Taking the Green Road) -** This scenario assumes a world that shifts toward a more sustainable and inclusive path, where people respect the environment and cooperate to achieve common goals. Education and health improve, population growth decreases, and inequality is reduced. Resource and energy use become more efficient and low-carbon, and environmental degradation is reversed. This scenario has a low level of challenges for both mitigation and adaptation.

- **SSP2: Dynamics as Usual (Middle of the Road) -** This scenario assumes a world that follows a moderate and uneven path, where social, economic, and technological trends do not change much from the past. Development and income growth vary across regions and countries, and some achieve more progress than others. Institutions and governance are adequate but not very

[32] Monterroso and Conde, "Exposure to Climate and Climate Change in Mexico."

effective in addressing global issues. Resource and energy use decline slightly, but environmental degradation continues. This scenario has a medium level of challenges for both mitigation and adaptation.

- **SSP3: Regional Rivalry (A Rocky Road)** - This scenario assumes a world that becomes more fragmented and unequal, where people focus on their own interests and security. Development and income growth are slow and uneven, and many countries face poverty and instability. Institutions and governance are weak and unable to cope with global challenges. Resource and energy use are high and inefficient, and environmental degradation is severe. This scenario has a high level of challenges for both mitigation and adaptation.

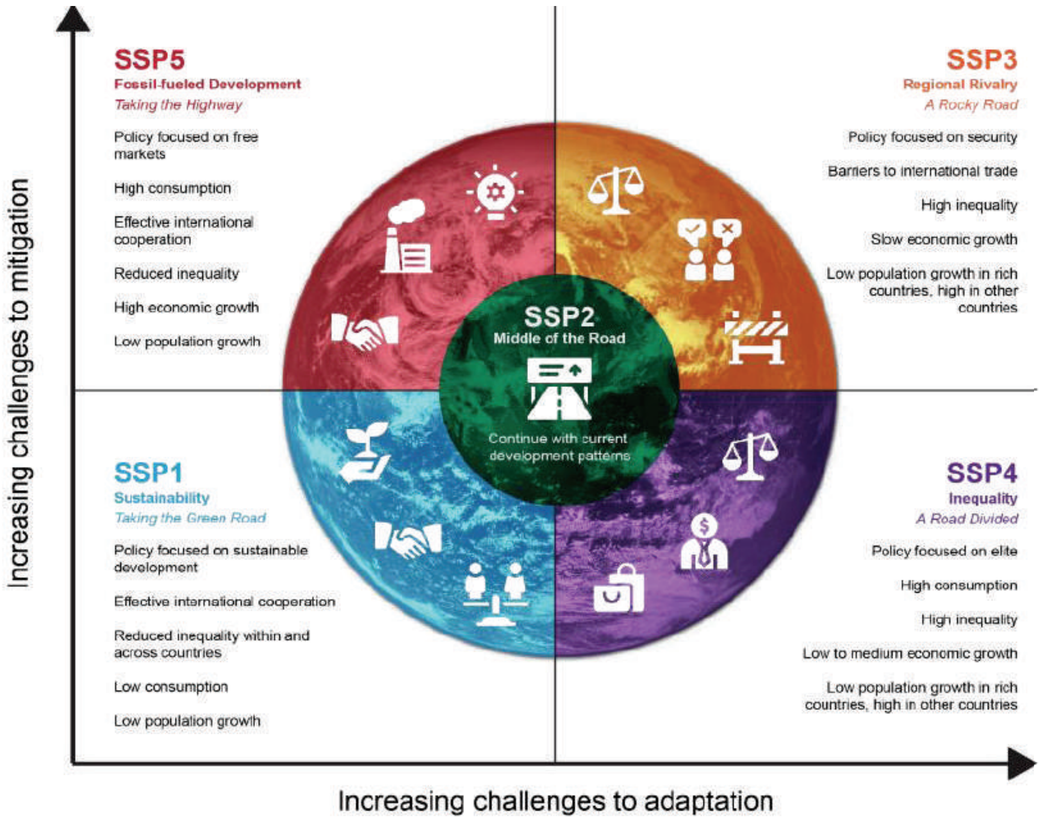


Figure 52 Shared Socio-economic Pathways [33]

[33] https://climatedata.ca/resource/understanding-shared-socio-economic-pathways-ssps/

Annexure II

Table 2 District wise projected mean change in total annual precipitation by 2040 from baseline under different climate change scenarios

NAME	Mean change SSP126 (mm)	Mean change SSP245 (mm)	Mean change SSP370 (mm)
Bumthang	14.06	11.53	14.83
Chhukha	21.48	19.02	25.08
Dagana	18.06	15.36	20.73
Gasa	38.34	17.82	24.85
Haa	22.79	19.62	30.82
Lhuentse	8.75	7.67	5.03
Monggar	-5.71	-2.55	-2.62
Paro	27.66	17.45	30.81
Pemagatshel	-10.71	-3.30	-4.78
Punakha	36.84	18.86	31.04
Samdrup Jongkhar	-22.92	-6.02	-12.59
Samtse	20.64	22.59	29.18
Sarpang	-1.56	5.62	7.25
Thimphu	29.12	16.81	29.93
Trashigang	-20.25	-6.84	-12.02
Trongsa	9.30	8.62	16.75
Tsirang	16.93	10.49	14.67
Wangdue Phodrang	22.67	14.67	25.09
Yangtse	-2.27	1.32	-4.35
Zhemgang	-5.50	-1.73	0.16

Table 3 District wise projected mean change in total annual precipitation from baseline by 2060 under different climate change scenarios

NAME	Mean change SSP126 (mm)	Mean change SSP245 (mm)	Mean change SSP370 (mm)
Bumthang	69.00	50.27	58.01
Chhukha	70.85	45.43	65.24
Dagana	72.33	42.10	64.05
Gasa	72.69	58.80	76.15
Haa	68.31	51.06	67.88
Lhuentse	60.30	43.38	44.17
Monggar	54.93	29.81	27.88
Paro	71.52	53.85	71.34
Pema Gatshel	55.18	26.43	28.08
Punakha	78.70	59.48	77.12
Samdrup Jongkhar	48.72	27.81	17.81
Samtse	66.27	48.33	63.83
Sarpang	66.21	31.43	50.81
Thimphu	72.76	55.96	73.59
Trashigang	45.54	29.88	15.94
Trongsa	71.33	45.04	56.31
Tsirang	70.95	37.53	57.98
Wangdue Phodrang	75.95	53.67	69.39
Yangtse	51.24	38.61	30.33
Zhemgang	59.93	27.20	36.60

Table 4 District wise projected mean change in total annual precipitation from baseline by 2100 under different climate change scenarios

NAME	Mean change SSP126 (mm)	Mean change SSP245 (mm)	Mean change SSP370 (mm)
Bumthang	92.38	150.80	348.57
Chhukha	103.77	121.69	341.57
Dagana	96.33	120.39	342.75
Gasa	103.74	162.18	356.36
Haa	113.42	148.80	369.30
Lhuentse	82.19	139.62	333.23
Monggar	72.75	114.37	320.96
Paro	111.21	156.99	376.86
Pema Gatshel	64.20	89.10	316.33
Punakha	110.03	171.15	380.73
Samdrup Jongkhar	60.29	83.64	307.08
Samtse	112.02	128.25	342.09
Sarpang	80.12	105.01	330.35
Thimphu	108.48	159.56	374.51
Trashigang	65.31	103.82	309.63
Trongsa	92.86	145.54	352.17
Tsirang	89.20	117.97	339.32
Wangdue Phodrang	101.72	157.56	364.73
Trashiyangtse	73.24	127.52	323.53
Zhemgang	72.96	103.93	323.56

Table 5 District wise projected mean change in total monsoon precipitation from baseline by 2040 under different climate change scenarios

NAME	Mean change SSP126 (mm)	Mean change SSP245 (mm)	Mean change SSP370 (mm)
Samtse	64.22	80.74	130.70
Chhukha	50.07	68.63	106.94
Haa	40.67	55.90	105.36
Punakha	46.98	65.75	103.08
Paro	39.65	55.50	99.78
Thimphu	41.14	57.17	97.35
Dagana	43.90	64.39	94.98
Wangdue Phodrang	40.33	58.27	92.55
Gasa	43.62	58.60	91.96
Tsirang	38.90	61.37	87.10
Sarpang	36.72	60.17	80.61
Trongsa	28.40	47.51	79.78
Bumthang	28.38	39.65	73.92
Lhuentse	19.03	26.86	61.37
Zhemgang	16.30	39.81	60.32
Monggar	3.02	20.14	48.27
Yangtse	6.27	12.51	47.63
Pema Gatshel	8.26	34.13	47.46
Samdrup Jongkhar	-1.94	23.41	37.77
Trashigang	-9.45	5.53	33.78

Table 6 District wise projected mean change in total monsoon precipitation from baseline by 2060 under different climate change scenarios

NAME	Mean change SSP126 (mm)	Mean change SSP245 (mm)	Mean change SSP370 (mm)
Dagana	80.74	66.33	92.37
Trongsa	65.75	52.15	87.80
Paro	58.60	51.11	81.26
Gasa	68.63	44.69	77.97
Tsirang	57.17	45.98	77.73
Samdrup Jongkhar	58.27	40.60	75.58
Samtse	55.50	43.91	74.74
Wangdue Phodrang	55.90	44.18	72.59
Thimphu	64.39	34.94	72.35
Monggar	61.37	28.87	67.39
Yangtse	60.17	25.06	62.72
Trashigang	47.51	25.25	59.40
Punakha	39.65	28.08	57.44
Haa	26.86	19.20	42.62
Pema Gatshel	39.81	7.36	38.93
Chhukha	34.13	2.31	26.02
Zhemgang	12.51	7.14	24.49
Bumthang	20.14	-1.89	21.79
Lhuentse	23.41	-2.64	10.65
Sarpang	5.53	-10.20	3.41

Table 7 District wise projected mean change in total monsoon precipitation from baseline by 2100 under different climate change scenarios

NAME	Mean change SSP126 (mm)	Mean change SSP245 (mm)	Mean change SSP370 (mm)
Trongsa	103.08	164.06	327.01
Samtse	99.78	148.34	318.71
Tsirang	97.35	150.10	317.72
Wangdue Phodrang	105.36	143.24	313.01
Dagana	130.70	148.98	312.89
Paro	91.96	150.54	303.40
Samdrup Jongkhar	92.55	143.13	301.81
Gasa	106.94	124.47	293.80
Thimphu	94.98	115.67	286.78
Monggar	87.10	110.38	280.03
Trashigang	79.78	122.48	277.31
Yangtse	80.61	99.10	270.40
Punakha	73.92	122.43	270.37
Haa	61.37	105.81	246.94
Pema Gatshel	60.32	80.78	243.69
Chhukha	47.46	60.68	225.19
Bumthang	48.27	73.72	221.71
Zhemgang	47.63	83.71	221.54
Lhuentse	37.77	45.70	200.06
Sarpang	33.78	51.03	190.84

Table 8 District wise projected mean change in average annual Tmax from baseline by 2040 under different climate change scenarios

NAME	Mean change SSP126 (°C)	Mean change SSP245 (°C)	Mean change SSP370 (°C)
Bumthang	1.36	1.29	1.30
Chhukha	1.11	0.97	0.96
Dagana	1.12	0.99	0.99
Gasa	1.47	1.41	1.41
Haa	1.21	1.10	1.09
Lhuentse	1.36	1.29	1.31
Monggar	1.20	1.10	1.12
Paro	1.28	1.20	1.19
Pemagatshel	1.13	0.99	1.00
Punakha	1.36	1.29	1.29
Samdrupjongkhar	1.13	0.98	1.00
Samtse	1.11	0.96	0.95
Sarpang	1.13	1.00	1.00
Thimphu	1.33	1.25	1.25
Trashigang	1.19	1.08	1.10
Trongsa	1.27	1.19	1.19
Tsirang	1.14	1.01	1.01
Wangduephodrang	1.31	1.24	1.24
Yangtse	1.32	1.23	1.26
Zhemgang	1.16	1.04	1.04

Table 9 District wise projected mean change in average annual Tmax from baseline by 2060 under different climate change scenarios

NAME	Mean change SSP126 (°C)	Mean change SSP245 (°C)	Mean change SSP370 (°C)
Bumthang	1.78	2.06	2.23
Chhukha	1.52	1.70	1.77
Dagana	1.54	1.72	1.81
Gasa	1.87	2.20	2.39
Haa	1.60	1.82	1.94
Lhuentse	1.78	2.07	2.25
Monggar	1.61	1.82	1.97
Paro	1.67	1.92	2.07
Pemagatshel	1.54	1.70	1.82
Punakha	1.75	2.04	2.21
Samdrupjongkhar	1.54	1.68	1.82
Samtse	1.52	1.69	1.76
Sarpang	1.54	1.72	1.82
Thimphu	1.71	1.99	2.15
Trashigang	1.60	1.79	1.96
Trongsa	1.68	1.93	2.08
Tsirang	1.55	1.75	1.84
Wangduephodrang	1.72	1.99	2.14
Yangtse	1.73	1.99	2.18
Zhemgang	1.57	1.76	1.88

Table 10 District wise projected mean change in average annual Tmax from baseline by 2100 under different climate change scenarios

NAME	Mean change SSP126 (°C)	Mean change SSP245 (°C)	Mean change SSP370 (°C)
Bumthang	1.96	3.15	4.43
Chhukha	1.71	2.78	3.83
Dagana	1.73	2.79	3.85
Gasa	2.06	3.31	4.73
Haa	1.79	2.92	4.10
Lhuentse	1.96	3.15	4.46
Monggar	1.78	2.88	4.02
Paro	1.86	3.03	4.28
Pemagatshel	1.70	2.76	3.81
Punakha	1.95	3.14	4.44
Samdrupjongkhar	1.69	2.75	3.79
Samtse	1.71	2.78	3.84
Sarpang	1.73	2.79	3.83
Thimphu	1.90	3.09	4.38
Trashigang	1.76	2.85	3.98
Trongsa	1.87	3.00	4.20
Tsirang	1.74	2.81	3.88
Wangduephodrang	1.91	3.07	4.32
Yangtse	1.90	3.07	4.34
Zhemgang	1.74	2.82	3.89

Table 11 District wise projected mean change in average annual Tmin from baseline by 2040 under different climate change scenarios

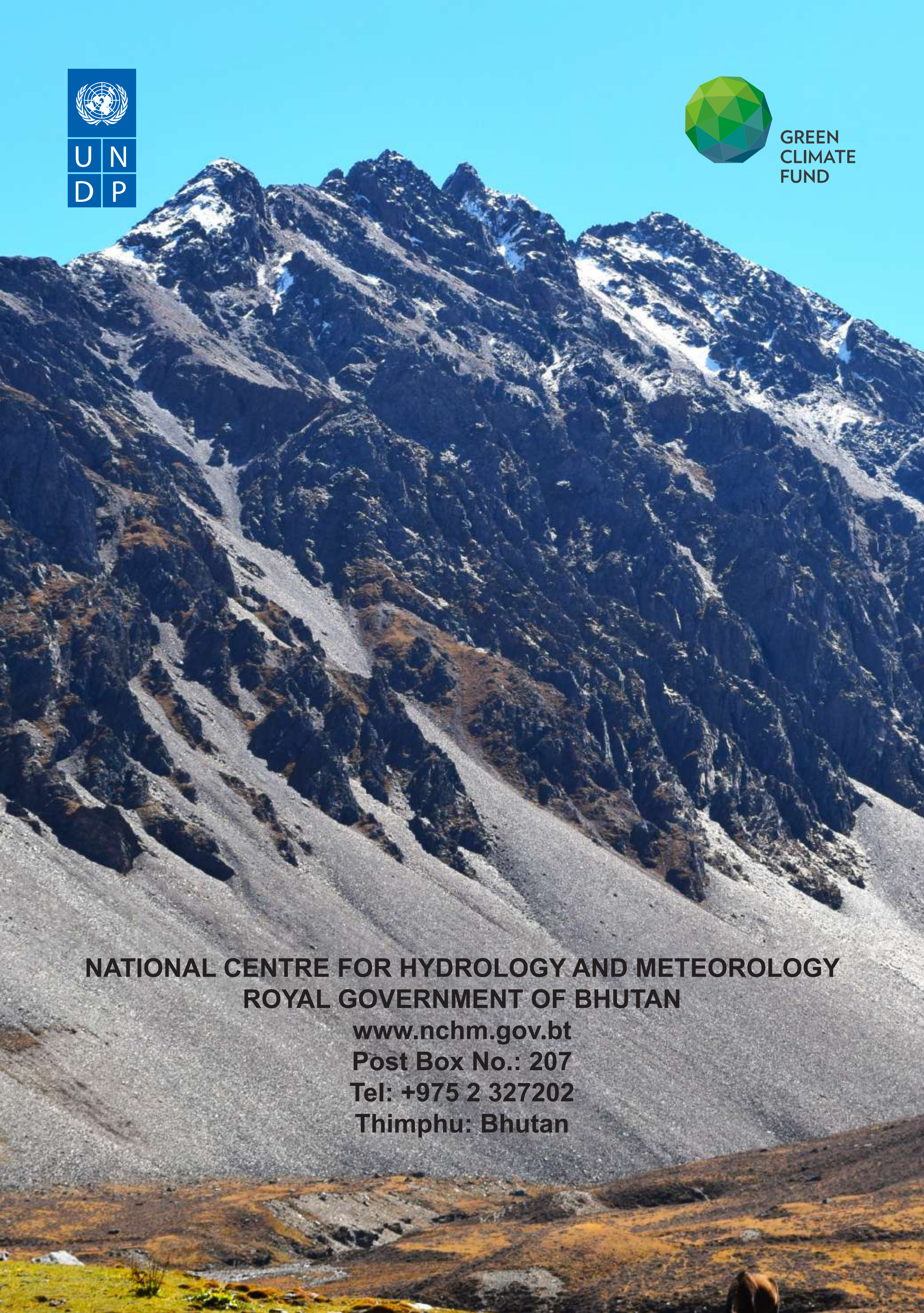
NAME	Mean change SSP126 (°C)	Mean change SSP245 (°C)	Mean change SSP370 (°C)
Bumthang	1.55	1.56	1.63
Chhukha	1.35	1.35	1.39
Dagana	1.34	1.35	1.38
Gasa	1.73	1.75	1.81
Haa	1.47	1.48	1.52
Lhuentse	1.58	1.58	1.66
Monggar	1.37	1.39	1.44
Paro	1.54	1.55	1.60
Pema Gatshel	1.31	1.32	1.36
Punakha	1.58	1.61	1.66
Samdrup Jongkhar	1.31	1.32	1.37
Samtse	1.37	1.37	1.40
Sarpang	1.32	1.32	1.36
Thimphu	1.57	1.60	1.64
Trashigang	1.37	1.38	1.44
Trongsa	1.44	1.46	1.51
Tsirang	1.34	1.34	1.38
Wangdue Phodrang	1.51	1.53	1.58
Yangtse	1.52	1.54	1.61
Zhemgang	1.32	1.34	1.38

Table 12 District wise projected mean change in average annual Tmin from baseline by 2060 under different climate change scenarios

NAME	Mean change SSP126 (°C)	Mean change SSP245 (°C)	Mean change SSP370 (°C)
Bumthang	2.00	2.38	2.65
Chhukha	1.81	2.10	2.31
Dagana	1.79	2.09	2.31
Gasa	2.20	2.60	2.92
Haa	1.92	2.24	2.50
Lhuentse	2.03	2.41	2.69
Monggar	1.82	2.13	2.37
Paro	1.99	2.34	2.61
Pema Gatshel	1.76	2.04	2.25
Punakha	2.03	2.41	2.69
Samdrup Jongkhar	1.76	2.04	2.26
Samtse	1.82	2.12	2.34
Sarpang	1.76	2.06	2.27
Thimphu	2.03	2.39	2.67
Trashigang	1.82	2.12	2.36
Trongsa	1.88	2.24	2.48
Tsirang	1.78	2.09	2.30
Wangdue Phodrang	1.96	2.33	2.59
Yangtse	1.98	2.34	2.61
Zhemgang	1.77	2.08	2.29

Table 13 District wise projected mean change in average annual Tmin from baseline by 2100 under different climate change scenarios

NAME	Mean change SSP126 (°C)	Mean change SSP245 (°C)	Mean change SSP370 (°C)
Bumthang	2.02	3.43	5.09
Chhukha	1.87	3.10	4.53
Dagana	1.85	3.08	4.51
Gasa	2.19	3.69	5.54
Haa	1.94	3.24	4.82
Lhuentse	2.06	3.48	5.14
Monggar	1.86	3.14	4.59
Paro	1.99	3.34	5.00
Pema Gatshel	1.82	3.04	4.41
Punakha	2.01	3.42	5.14
Samdrup Jongkhar	1.83	3.04	4.40
Samtse	1.89	3.13	4.58
Sarpang	1.83	3.05	4.45
Thimphu	2.02	3.41	5.10
Trashigang	1.86	3.13	4.56
Trongsa	1.90	3.23	4.79
Tsirang	1.84	3.08	4.50
Wangdue Phodrang	1.96	3.33	4.97
Yangtse	2.01	3.40	4.99
Zhemgang	1.83	3.07	4.48



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